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Research Record

Evaluation of Pier-Scour Measurement Methods and Pier-Scour Predictions with Observed Scour Measurements at Selected Bridge Sites in New Hampshire, 1995-98

Final Report – November 2000

Prepared by the U.S. Geological Survey, NH/VT District, for the New Hampshire Department of Transportation, in cooperation with the U.S. Department of Transportation, Federal Highway Administration

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16. Abstract

In a previous study, 44 of 48 bridge sites examined in New Hampshire were categorized as scour critical. This report summarizes research conducted to evaluate pier-scour measurement methods and predictions at many of these sites. This evaluation included measurement of pier-scour depths at 20 sites using ground-penetrating radar (GPR). Pier-scour was also measured during floods by teams at 5 of these 20 sites. At 4 of the 20 sites, fixed instruments were installed to monitor scour.

At only one bridge site investigated by a team was any pier scour measurable during a flood event. Measurements made using GPR and/or fixed instruments indicated pier scour at 6 sites. The GPR surveys indicated scour along the pier side and further upstream from the nose that was not detected by flood-team measurements at 2 sites.

Most pier-scour equations selected for this examination were reviewed and published in previous scour investigations. Graphical comparisons of residual pier-scour depths indicate that the Shen equation yielded scour depth predictions closest to those measured, without underestimating. Measured depths of scour, however, were zero feet for 14 of the 20 sites. For the Blench-Inglis II equation and the Simplified Chinese equation, most differences between measured and predicted scour depths were within 5 feet. These two equations underpredicted scour for one of six sites with measurable scour. The underprediction, however, was within the resolution of the depth measurements.

The Simplified Chinese equation is less sensitive than other equations to velocity and depth input variables, and is one of the few empirical equations to integrate the influence of flow competence, or a measure of the maximum streambed particle size that a stream is capable of transporting, in the computation of pier scour. Absence of a flow-competence component could explain some of the overprediction by other equations, but was not investigated in this study. Measurements of scour during large floods at additional sites are necessary to strengthen and substantiate the application of alternatives to the HEC-18 equation to estimate pier scour at waterway crossing in New Hampshire.

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Cover photographs from left to right, clockwise: Lamprey River flood at State Route 102 Bridge in Raymond, N.H., October 1996. (Photograph by Erick Boehmler, U.S. Geological Survey); Ossipee River flood at State Route 153 Bridge in Effingham Falls, N.H., June 1998. (Photograph by Ronda Burns, U.S. Geological Survey); Lamprey River flood at Wiswall Rd. Bridge in Durham, N.H., October 1996. (Photograph by Richard Kiah, U.S. Geological Survey)

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Pembroke, New Hampshire
2000

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Temperature in degrees Fahrenheit (^oF) can be converted to degrees Celsius (^oC) as follows: $^oC = 5/9\ (^oF - 32)$.

Vertical Datum: In this report “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

OTHER ABBREVIATIONS USED IN THIS REPORT

kHz	=	kilohertz
MHz	=	megahertz
lbs	=	pound
kg	=	kilogram
mm	=	millimeter
kg/s^2	=	kilogram per square second
kg/m^3	=	kilogram per cubic meter
lb/ft^3	=	pound per cubic foot
Q10	=	10-year flood discharge
Q100	=	100-year flood discharge

EQUATION SYMBOLS USED IN THIS REPORT

b	Pier width.
D_n	Diameter of particles for which n percent are smaller in the bed material.
F_0	Froude number of the flow immediately upstream of a pier.
F_c	Critical Froude number for flow at the incipient motion velocity.
g	Acceleration due to gravity.
K_1	A coefficient based on pier shape.
K_2	A coefficient based on the angle of attack of approaching flow and the ratio of pier length to pier width.
K_3	A coefficient based on the streambed condition.
K_4	A coefficient based on armoring by larger particles in the bed material.
K_I	A coefficient based on flow intensity.
K_d	A coefficient based on the median particle diameter of the bed material.
K_y	A coefficient based on flow depth immediately upstream of a pier.
L	Pier length.
p	Local momentum of a 1-meter-wide column of water immediately upstream of a pier.
ρ	Density of water at a pier.
u_{*c}	Critical shear velocity for the bed material particles.
V_a	Critical velocity of flow for armor layer bed material.
V_{ca}	Critical velocity of flow for the D_{50} of the armor layer particles.
V_c	Critical velocity of flow when the D_{50} begins to move.
$V_{c(D_n)}$	Critical velocity of flow at which particles of diameter D_n begin to move.
V_0	Velocity of flow immediately upstream of a pier.
V_i	Incipient motion velocity of the D_n size bed material particles.
V_R	A dimensionless velocity ratio in computation of K_4.
w	Width of flow immediately upstream of a pier.
y_{sp}	Depth of scour at a pier.
y_0	Depth of flow immediately upstream of a pier.
τ_c	Critical tractive force of the D_{50}.
σ	Standard deviation (D) approximation of bed material particle size computed by $\frac{(D_{84} - D_{16})}{4} + \frac{(D_{95} - D_5)}{6.6}$.

Evaluation of Pier-scour Measurement Methods and Pier-scour Predictions With Observed Scour Measurements at Selected Bridge Sites in New Hampshire, 1995-98

By Erick M. Boehmler *and* Joseph R. Olimpio

Abstract

In a previous study, 44 of 48 bridge sites examined in New Hampshire were categorized as scour critical. In this study, the U.S. Geological Survey (USGS) evaluated pier-scour measurement methods and predictions at many of these sites. This evaluation included measurement of pier-scour depths at 20 bridge sites using Ground-Penetrating Radar (GPR) surveys. Pier scour was also measured during floods by teams at 5 of these 20 sites. At 4 of the 20 sites, fixed instruments were installed to monitor scour.

At only one bridge site investigated by a team was any pier scour measurable during a flood event. A scour depth of 0.7 foot (0.21 m) was measured at a pier in the channel at the State Route 18 bridge over the Connecticut River in Littleton. Measurements made using GPR and (or) fixed instruments indicated pier scour for six sites. The GPR surveys indicated scour along the side of a pier and further upstream from the nose of a pier that was not detected by flood-team measurements at two sites.

Most pier-scour equations selected for this examination were reviewed and published in previous scour investigations. Graphical comparison of residual pier-scour depths indicate that the Shen equation yielded pier-scour depth predictions closest to those measured, without underestimating. Measured depths of scour, however, were zero feet for 14 of the 20 sites. For the Blench-Inglis II equation and the Simplified Chinese equation, most differences between measured and predicted scour depths were within 5 feet. These two equations underpredicted scour for one of six sites with measurable scour. The underprediction, however, was within the resolution of the depth measurements.

The Simplified Chinese equation is less sensitive than other equations to velocity and depth input variables, and is one of the few empirical equations to integrate the influence of flow competence, or a measure of the maximum streambed particle size that a stream is capable of transporting, in the computation of pier scour. Absence of a flow-competence component could explain some of the overprediction by other equations, but was not investigated in this study. Measurements of scour during large floods at additional sites are necessary to strengthen and substantiate the application of alternatives to the HEC-18 equation to estimate pier scour at waterway crossings in New Hampshire.

INTRODUCTION

In a report published for the New Hampshire Department of Transportation (NHDOT) (Whitman & Howard, Inc., 1992), 44 of 48 bridge sites evaluated in the State were categorized as scour critical; 35 of the 48 bridge sites were categorized as scour critical for discharges equal to or exceeding the 10-year recurrence interval. However, the historically low occurrence of damage to these bridges prompted initiation of a cooperative investigation between the

U.S. Geological Survey (USGS) and NHDOT to evaluate streambed scour at piers using a variety of monitoring methods.

Since the 1987 collapse of the New York State Thruway bridge crossing Schoharie Creek, extensive research has been conducted on bridge-scour processes. The understanding of scour processes, however, remains poor for locations with coarse, non-uniformly graded streambed material. Scour-prediction equations currently (1999) recommended by the U.S. Department of Transportation, Federal Highway Administration (FHWA), are based mostly on laboratory data. Continued collection and analysis of scour data at bridge sites is necessary for the development of improved methods to measure, monitor, and predict scour at bridges.

From 1996 through 1998, streamflow and associated scour measurements were made during at least one flood at five scour-critical bridges in New Hampshire. Pier-scour measurements by fixed recording instrumentation also were made at four sites. Ground Penetrating Radar (GPR) was used to measure any scour that occurred between April 1996 and November 1998 for 20 sites, including those at which scour measurements were made by flood teams and fixed instruments.

Purpose and Scope

This report documents streambed measurements made along cross sections at 20 bridges in New Hampshire. The measurements were used to determine pier-scour depths and to compare measured pier-scour depths with those predicted by use of a variety of documented pier-scour equations. The report also describes the scour-monitoring methods used and evaluates and compares the methods. Comparisons of the differences between measured and predicted pier scour, called residuals, are presented.

Predictions of scour-depth at piers are computed by use of equations developed and documented by Ahmad (1953); Blench (1951, 1962, and 1969); Gerald Butch (U.S. Geological Survey, written commun., 1998); Gao and others (1993); Inglis (1949); Maza and Sanchez (1964); Melville and Sutherland (1988); Richardson and Davis (1995); Richardson and others (1990); Shen and others (1966); and Jain and Fischer (1979). These equations were selected to focus on pier-scour predictions for which streambed material size and (or) flow velocity were considered in the equation development. Landers and Mueller (1996) and Mueller (1996) provide insights to the research and development of most of these equations.

Site Selection

Whitman & Howard, Inc. (1992) identified 44 scour-critical bridges that were considered for further investigation as part of this project. In April 1996, GPR was used to examine 39 of these sites. Initial selection of sites for GPR surveys was made on the basis of streambed characteristics that were conducive to investigations by GPR methods. Review of the initial round of GPR survey results indicated that 20 sites had interpretable GPR images, and these sites were resurveyed in November 1998 to identify changes attributable to scour.

Flood teams were deployed to sites when the discharge at nearby streamflow-gaging stations exceeded the 2-year recurrence interval. When the number of sites experiencing flooding exceeded the number of teams available, sites were prioritized according to anticipated magnitude of flooding and site characteristics. Site characteristics considered were bed material size, presence or lack of stone-fill protection, angle of attack on the bridge pier(s), width and type of pier, and streambed gradient through the stream reach. Discharges in excess of the 2-year recurrence interval occurred at five sites during the investigation. Thus, multiple measurements of discharge and scour were made by flood teams at all five sites. At two sites, scour-monitoring measurements were made during each of two flood events.

Sites for fixed-instrument operation were selected on the basis of the following criteria: (1) piers are reasonably aligned (within 15 degrees) with the streamflow direction, (2) the stream reach upstream from the pier is straight (no abrupt turns before entering the bridge section), (3) the bridge site is easily accessible, (4) the bridge pier is not placed on bedrock, (5) a USGS streamflow-gaging station is nearby to allow estimates of discharge, thereby providing a means to estimate flow velocity and depth at piers, and (6) the piers are not susceptible to debris accumulation. Of the 20 sites examined in this report, fixed instruments were mounted to piers at sites 3, 5, 8, and 11. The locations of all 20 sites monitored by various methods as part of the study are shown in figure 1 and selected site characteristics are compiled in table 1. Some additional site characteristics and descriptions for the 20 bridge sites are listed in appendix 1.

DATA COLLECTION AND COMPILATION

Four sources of scour data were used in this investigation: (1) data collected by fixed instruments, (2) results of geophysical surveys, (3) observations and measurements made by flood teams, and (4) data from previous studies. In this section, data collection by each source is described in detail. Data collection by GPR is described briefly below, but is evaluated and documented in more detail by Olimpio (2000). Establishment of reference points, datums, and scour-reference surfaces also is described in this section.

Scour Measurements by Fixed Instruments

Many types of fixed scour-monitoring devices are available for measurement of local scour around bridge piers. An overview of the various types of fixed instruments is presented by Trent and Friedland (1992). The National Cooperative Highway Research Program completed a project (Richardson and Lagasse, 1992), in which various fixed monitoring devices were evaluated from technical and economic aspects. Many of these devices were used successfully by the USGS at bridges nationwide. The most common types are mechanical sliding collar devices, sliding rods, and various sonar (echo sounder) instruments.

Three sonar instruments and one mechanical sliding rod device were installed at the upstream end of piers. Where there were multiple piers in the flood-flow channel, the monitoring device was mounted to the pier at which the greatest scour was predicted (Whitman & Howard, Inc., 1992). The sonar instruments consisted of a Datasonics PSA-902 acoustic altimeter with two 8-degree transducers mounted to two of four piers (piers 2, 3) at site 11 in Littleton (table 1). Raytheon ST-50 depth sounders coupled to Campbell Scientific CR-10 data recorders and 8-degree transducers were installed on pier 1 at site 3 in Clarksville (table 1) and on pier 1 at site 5 in Effingham (table 1). A Brisco Monitor sliding rod device was installed on pier 1 at site 8 in Lincoln (table 1).

Datasonics PSA-902 Acoustic Altimeter

The Datasonics PSA-902 acoustic altimeter is a multichannel sonar ranging system designed to make up to 16 sequential sonar range measurements by echo sounding. The system is micro-processor controlled, interfaces directly with a portable computer through a standard RS-232 port, and is designed to store measurements made at 30-minute intervals on a random access memory (RAM) card. Two 8-degree transducers were installed on piers 2 and 3 at site 11 in Littleton, and connected by cables routed up the pier, along the bridge structure, and connected to the Datasonics PSA-902 instrument, which was mounted on the bridge rail and housed in a protective shelter. Transducers were installed at a known elevation above the streambed, on the upstream edge of the piers. The transducers at piers 2 and 3 were mounted vertically [6.0 ft (1.83 m) and 5.5 ft (1.68 m)] above the stone-fill protection on each pier, respectively. Data collection began in October 1996, and data was downloaded approximately once every 3 months. Measurements of pier scour at this site, using the sonar ranging system, were not compared with estimates from the equations due to the difference in the influence of scour processes on the stone fill and that on the native streambed material.

Raytheon ST-50 Depth Sounder

The Raytheon ST-50 depth-sounding instrument is a low cost, single-channel sonar ranging device designed to make one range measurement per sample interval by echo-sounding. The instrument is connected to a Campbell Scientific CR-10 data logger that is programmed to log data at 30-minute intervals. One 8-degree transducer was installed at a fixed known elevation on the upstream end of the pier at site 3 in Clarksville and another on pier 1 at site 5 (fig. 1, table 1) in Effingham. The transducers were connected by cables routed up the nose of the pier, across the bridge structure, and connected to the Raytheon instruments and data loggers, which were located on the bridge rails in protective shelters. The stream-depth data measured were downloaded to a portable computer once every 3 months. Data collection began in October 1996.

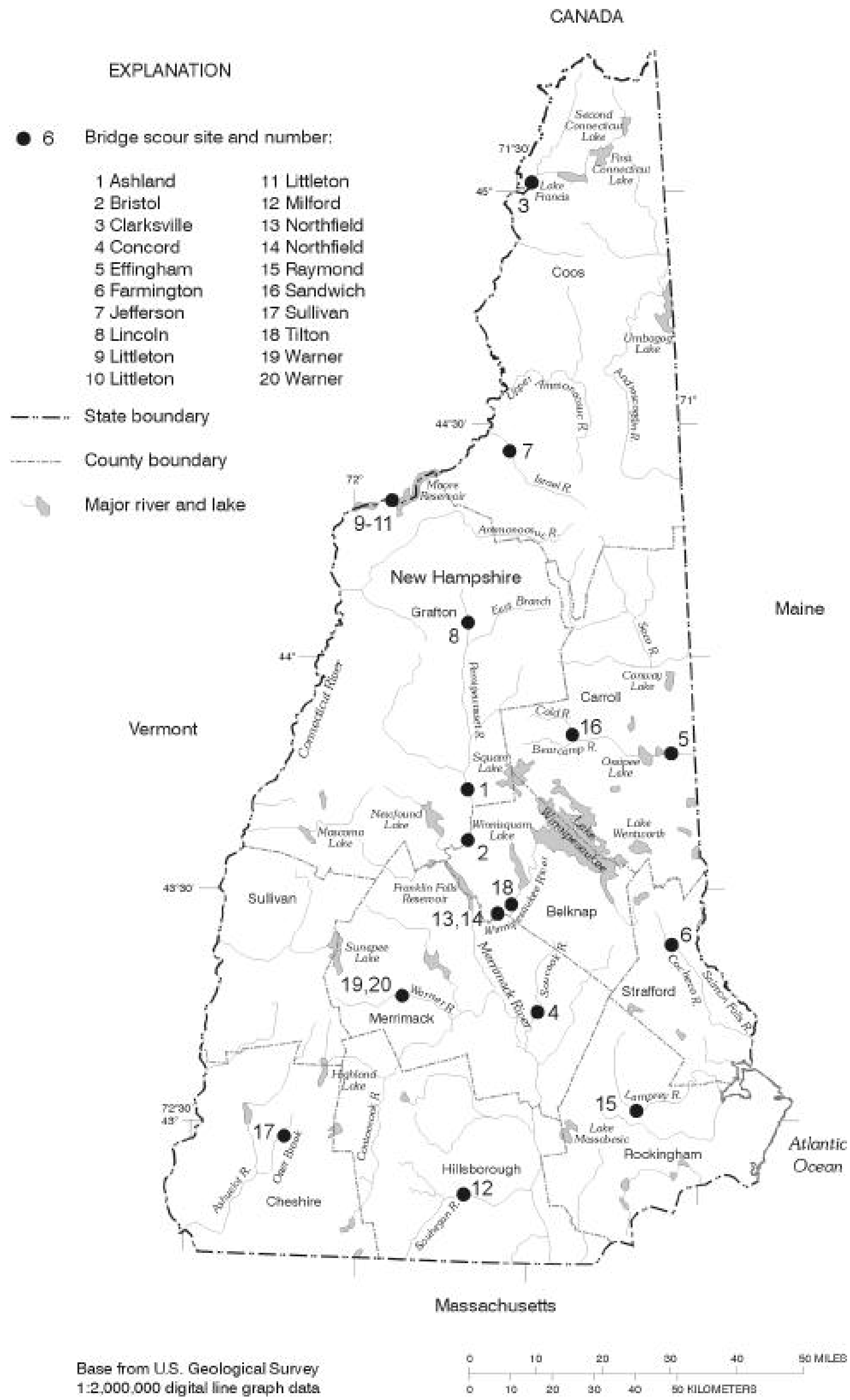

Figure 1. Location of New Hampshire bridge scour study sites.

Table 1. Some descriptive characteristics of examined bridge locations in New Hampshire

[US, United States Route; N.H., State Route; I, Interstate Route; GPR, Ground-Penetrating Radar; FI, Fixed Instrument; FT, Flood Team; Solid, pier material is continuous from upstream to downstream end (i.e. no piles or columns); Hammer, pier is solid and longer at the bottom such that the ends of the pier slope at an angle less than vertical; Column, pier material is discontinuous from upstream to downstream end such that support of bridge is on two or more of these with space between columns]

Site No. (fig. 1)	Structure No.	Town	County	Road or route	River name	Measurements	No. of piers	Pier type
1	076/080	Ashland	Grafton	US 3/N.H. 25	Pemigewasset	GPR	8	Solid
2	183/087	Bristol	Grafton	N.H. 104	Pemigewasset	GPR	2	Hammer
3	030/066	Clarksville	Coos	US 3	Connecticut	GPR, FI	1	Solid
4	160/188	Concord	Merrimack	N.H. 9	Soucook	GPR, FT	2	Column
5	110/190	Effingham	Carroll	N.H. 153	Ossipee	GPR, FI, FT	2	Solid
6	096/140	Farmington	Strafford	N.H. 153	Cocheco	GPR	1	Solid
7	046/178	Jefferson	Coos	US 2	Israel	GPR	1	Solid
8	202/100	Lincoln	Grafton	I-93 Northbound Exit Ramp	Pemigewasset	FI, GPR	1	Solid
9	104/136	Littleton	Grafton	I-93 Southbound	Connecticut	GPR	3	Solid
10	105/135	Littleton	Grafton	I-93 Northbound	Connecticut	GPR	3	Solid
11	109/134	Littleton	Grafton	N.H. 18	Connecticut	GPR, FI, FT	4	Column/solid
12	123/133	Milford	Hillsborough	N.H. 13	Souhegan	GPR	1	Solid
13	117/157	Northfield	Merrimack/Belknap	I-93 Southbound	Winnipesaukee	GPR	3	Hammer
14	118/158	Northfield	Merrimack/Belknap	I-93 Northbound	Winnipesaukee	GPR	3	Hammer
15	146/100	Raymond	Rockingham	N.H. 107	Lamprey	GPR, FT	1	Hammer
16	238/092	Sandwich	Carroll	N.H. 113	Cold	GPR, FT	1	Solid
17	093/061	Sullivan	Cheshire	N.H. 9	Otter Brook	GPR	1	Solid
18	109/062	Tilton	Belknap/Merrimack	N.H. 140	Winnipesaukee	GPR	1	Solid
19	166/103	Warner	Merrimack	I-89 Southbound	Warner	GPR	2	Column
20	166/104	Warner	Merrimack	I-89 Northbound	Warner	GPR	2	Column

Brisco Monitor Sliding Rod Device

The Brisco Monitor sliding rod device utilizes a simple mechanical principle. A small diameter sliding steel rod encased in a polyvinylchloride (PVC) conduit moves freely within a stationary steel conduit attached to the bridge pier. The sliding rod acts as a probe, resting on the streambed in front of the bridge pier. As the bed material washes away, the sliding rod drops a measured distance. The distance that the rod falls is measured by means of a cable attached from the top of the sliding rod to a counter housed in a weatherproof enclosure. The counter has a digital display, which shows the distance in feet the rod has fallen. This instrument was installed at site 8 (fig. 1, table 1) in Lincoln. There is no data-recording instrument at this site, therefore, a manual counter reading was made once every 3 months or immediately following a significant streamflow event.

Scour Measurements by Geophysical Methods

Surface geophysical methods have been used for the delineation of the areal extent and depth of scour at bridge sites (Placzek and Haeni, 1995). Several geophysical methods, including color fathometer, tuned transducer, black and white fathometer, and ground-penetrating radar (GPR), can provide a profile of the streambed and sub-streambed characteristics and can be effective scour-monitoring tools. In this study, a chart-recording fathometer and a digital GPR system were used.

Fathometer

Small boat fathometers (depth finders) use a sonar pulse to measure water depth and streambed topography. A chart-recording, fathometer operating at 192 kHz was used to measure streambed elevation, topography, and scour holes during flood events. An 8-degree transducer was mounted in a commercially available knee-board that served as a floating deployment platform. The knee-board was connected to the fathometer by electrical cable and rope. This arrangement was deployed over the upstream and downstream sides of the bridge and guided (by an operator standing on the bridge deck) by rope across the surface of the water at the bridge opening. This floating platform allowed data to be collected quickly and the length of the guiding rope could be adjusted to extend the area covered downstream of the bridge opening along bridge piers and abutments. Notes regarding pier locations, debris, or other important features were placed directly on the paper chart as the data were collected.

Ground-Penetrating Radar

From April through June 1996, and from October through November 1998, Ground-Penetrating Radar was used to measure the depth and extent of existing and infilled scour holes, and streambed and sub-streambed characteristics at bridge sites. Data interpretation was supported with information on bridge plans provided by the NHDOT. Depths to buried stone-fill materials and pier footings were identified and verified with bridge plans (David Powelson, New Hampshire Department of Transportation, written commun., November 1995).

The GPR system used a 300-MHz signal. Radar signals penetrated and measured water up to 18 ft (5.5 m) deep and streambed material up to 25 ft (7.6 m) thick, although increased water depth generally reduced the depth of streambed penetration. Scour surfaces, scour-hole dimensions, infilled sediment thickness and changes between the initial GPR survey in 1996, and the final GPR survey in 1998 were detected using this technique (Olimpio, 2000).

Initially, GPR techniques were applied at 39 bridge sites. The selection of bridge sites for later resurvey was based on the occurrence of a flood in excess of the 2-year recurrence interval discharge and the interpretability of the record. Resurveys were conducted at 20 of the 39 pre-flood surveyed bridge sites. Seven of the 20 sites depicting the best GPR record are examined, compared and documented in Olimpio (2000). GPR profiles included sections along each side of a pier, as well as across the channel at the bridge openings and ends of each pier. Data-processing techniques were applied to assist in the interpretation of the data. However, data processing was kept to a minimum, some interference from multiple reflections was left in the record, and the processed data were displayed and printed as line plots.

Scour Measurements by Flood Teams

Two teams made scour and discharge measurements during flood events at selected bridges. Discharges with recurrence intervals of 2 years or greater were estimated by use of real-time streamflow data (U.S. Geological Survey, 1996) at nearby streamflow-gaging stations. Flood teams included a minimum of two field personnel, but occasionally required one to two additional personnel for traffic control.

Each team was equipped with a type-E sounding reel fastened to a boom crane that was mounted to each vehicle. The E-reels were equipped with a battery-powered lift mechanism. Depth and velocity soundings were made by suspending a 150-pound weight (68 kg) and a Price type AA velocity meter from the E-reel cable (fig. 2). Standard streamflow-measurement procedures by Rantz and others (1982) were used except as required to measure scour variables at piers. Methods for obtaining limited detail scour data, as documented by Landers and Mueller (1996), were utilized.

Multiple streamflow and scour measurements were made during floods at five bridge sites. Measurements were made from the upstream and downstream sides of a bridge, alternating whenever possible, to more fully define any scour near the pier. Measurements of depth (immediately upstream) and velocity (approaching the pier and outside of turbulent and accelerated flow areas) at the upstream end of a pier were later applied in the pier-scour equations. There were a total of 34 measurements of depth and velocity of flow approaching 8 piers at the 5 sites (table 2). Each measurement of flow depth and velocity was made from the same location (horizontal stationing and distance above or below the bridge opening) on the bridge.

Measurements of stream discharge, water-surface elevation, and surface-flow directions near piers, also were made at each of the five sites. Water-surface measurements were made by measuring

(Photograph by: Joseph Olimpio, U.S.Geological Survey)

Figure 2. Equipment used to measure river discharge from bridges in New Hampshire—crane mounted on vehicle with an E-reel, Price-type AA velocity meter, and a 150-pound sounding weight.

the distance, using a steel tape, from a reference point on the bridge to the water surface. For the site in Effingham on the Ossipee River (table 1), river stage also was recorded at a streamflow-gaging station.

Surface-flow directions were measured by use of a protractor and verified with angles of attack applied in the scour analyses reported by Whitman & Howard, Inc. (1992). Photographs of the flood-flow conditions and observations, such as debris accumulation, were noted by flood teams. Site descriptions and conditions at the time of the flood measurements are provided in appendix 1.

Existing Data

Existing cross-sectional data at the five sites at which flood teams made measurements were obtained from previous studies. For sites numbered 5, 11, and 16 in table 1 (fig. 1), historical cross-sectional data at the bridge were acquired from surveys conducted by Whitman & Howard, Inc. (1992). Ground-geometry data for the bridge cross sections were taken from computer input files formatted for the Water Surface Profile (WSPRO) model (Shearman, 1990). For the sites numbered 4 and 15 (table 1), bridge cross-section data were extracted from input files of hydraulic models developed for flood-insurance studies. Flood-insurance-study records were obtained from the Federal Emergency Management Agency (FEMA). Additional bridge cross-section data were obtained from bridge plans that included elevation contour lines near each site. Ground-geometry coordinates were determined by measuring the distance along the center-line of the bridge from the left end of the bridge to each contour line.

Other data for all sites analyzed in this study were extracted from scour computations by Whitman & Howard, Inc. (1992). Data included the total discharges modeled, and the approach-flow velocities and depths at each pier. Relations of velocity and depth to discharge were estimated for piers at each site by interpolating data from the Whitman & Howard,

Table 2. Selected hydraulic characteristics, flood discharges, and measured pier-scour depths for bridge sites in New Hampshire

Site No. (fig. 1)	Parameters							Pier No.	Variables		Pier scour	
	Pier shape	Pier length (L), in ft	Pier width, (b), in ft	Angle of attack, in degrees	Median particle diameter, (D_{50}), in mm	Discharge-measurement date	Discharge, in ft^3/s		Flow depth, (y_0), in ft	Velocity, (V_0), in ft/s	Depth (ft)	Method of collection
1	Round	37	10	5	50	--	e22,500	7	e17.0	e5.2	2.3	GPR
2	Sharp	36	6.0	0	0.47	--	e25,000	1	e34.1	e2.7	.0	GPR
								2	e30.5	e4.4	.0	GPR
3	Sharp	43.5	5.0	5	28	3/31/1998	5,270	1	e4.4	e12.3	.0	GPR
								1	e4.4	e12.3	.7	FI
4	Square	61	5.0	5	7.5	10/22/1996	1,690	1	8.4	1.9	--	FT
								2	5.6	1.5	--	FT
						6/16/1998	1,150	1	6.5	1.6	--	FT
								2	4.0	0.7	--	FT
						6/17/1998	2,120	1	8.5	1.3	.0	FT
								1	e10.1	e3.9	.0	GPR
								2	6.5	1.6	.0	FT
								2	e10.1	e3.9	1.1	GPR
						6/18/1998	1,240	1	5.8	2.1	.0	FT
								2	4.8	0.6	.0	FT
5	Sharp	25	2.0	15	55	6/15/198	6,220	1	6.2	3.7	--	FT
								2	6.7	5.8	--	FT
						6/16/1998	6,910	1	6.8	3.3	.0	FT
								2	7.2	6.4	.0	FT
						6/17/1998	7,690	1	7.2	4.0	.0	FT
								1	e9.1	e4.1	.0	GPR
								1	e9.1	e4.1	.0	FI
								2	8.1	6.4	.0	FT
5	Sharp	25	2.0	15	55	6/17/1998	7,690	2	e10.4	e4.4	0.0	GPR
						6/18/1998	6,850	1	6.8	3.6	.0	FT
								2	7.4	6.4	.0	FT
						6/19/1998	5,960	1	6.4	3.5	.0	FT
								2	6.6	5.6	.0	FT
6	Sharp	41	3.0	0	25	--	e1,900	1	e7.7	e6.7	.0	GPR
7	Sharp	56	4.5	0	53	--	e6,400	1	e8.9	e12.6	.0	GPR
8	Sharp	46.2	4.7	0	80	--	e3,000	1	e6.2	e9.8	.0	FI
9	Sharp	30	6.3	0	80	4/2/1998	44,300	2	e14.4	e9.3	.0	GPR
								3	e14.6	e9.2	.0	GPR
10	Sharp	30	6.3	0	80	4/2/1998	44,300	2	e17.6	e9.5	.0	GPR
								3	e11.8	e7.0	.0	GPR

Table 2. Selected hydraulic characteristics, flood discharges, and measured pier-scour depths for bridge sites in New Hampshire—Continued

Site No. (fig. 1)	Parameters							Pier No.	Variables		Pier scour	
	Pier shape	Pier length (L), in ft	Pier width, (b), in ft	Angle of attack, in degrees	Median particle diameter, (D_{50}), in mm	Discharge-measurement date	Discharge, in ft^3/s		Flow depth, (y_0), in ft	Velocity, (V_0), in ft/s	Depth (ft)	Method of collection
11	Round	42	6.4	15	80	4/30/1996	14,800	2	10.9	5.6	--	FT
								3	8.1	2.9	--	FT
						4/2/1998	38,700	2	13.5	9.4	--	FT
								3	10.5	8.0	--	FT
						4/2/1998	44,300	2	14.2	8.6	.7	FT
								2	e12.5	e7.9	1.7	GPR
								2	e12.5	e7.9	.3	FI
								3	11.7	7.7	.7	FT
								3	e15.2	e9.2	2.3	GPR
								3	e15.2	e9.2	.0	FI
11	Round	42	6.4	15	80	4/3/1998	33,800	2	16.5	6.5	0.0	FT
								3	12.7	6.3	.0	FT
12	Sharp	40	8	0	0.37	--	e4,900	1	e8.4	e5.9	2.0	GPR
13	Sharp	38	5	5	16	6/28/1998	3,940	1	e5.4	e3.4	.0	GPR
								2	e12.0	e3.4	.0	GPR
14	Sharp	31.5	5	5	16	6/28/1998	3,940	1	e3.0	e3.3	.0	GPR
								2	e11.2	e3.3	.0	GPR
15	Sharp	38	2.5	5	65	10/21/1996	879	1	4.1	4.7	--	FT
						10/21/1996	1,560	1	6.0	5.9	.0	FT
						10/21/1996	2,020	1	6.5	6.4	.0	FT
								1	e5.4	e8.2	.0	GPR
						10/23/1996	1,620	1	5.9	5.7	.0	FT
						10/24/1996	804	1	3.8	5.9	.0	FT
16	Sharp	33	2.5	5	38	6/14/1998	4,450	1	7.7	6.1	--	FT
								1	e9.4	e5.8	1.4	GPR
						6/14/1998	3,790	1	7.5	5.8	.0	FT
						6/15/1998	1,230	1	4.5	2.9	.0	FT
17	Sharp	49	2.0	10	79	--	e1,300	1	e6.0	e7.8	.0	GPR
18	Sharp	48	2.5	0	30	6/28/1998	3940	1	e7.7	e5.8	.0	GPR
19	Cylinder	67	3.0	10	21	--	e2,000	1	e8.6	e4.2	.0	GPR
								2	e8.6	e4.2	.0	GPR
20	Cylinder	49.5	3.0	10	21	--	e2,000	1	e7.5	e3.9	.0	GPR
								2	e7.5	e3.9	.0	GPR

Inc. (1992) models. For flood discharges less than the Q_{10}, relations were extrapolated based on the slope of the relation between the Q_{10} and Q_{50}.

Selected hydrologic characteristics for watersheds above the examined bridge sites are provided in table 3. Scour prediction by the various methods evaluated in this study requires estimates of flow depth and velocity at bridge piers. These were obtained using the relations with discharge as described above. Discharges for flood events were obtained using several approaches. For the five sites with flood-team measurements (table 1), the discharges were measured directly. For sites 3, 13, 14, and 18 (table 2), the maximum discharge during the period April 1996 through November 1998, was obtained from a nearby streamflow-gaging station on the same stream. For the remaining sites, the maximum peak discharges during the study period were estimated by use of a drainage-area relation between the bridge site and a nearby streamflow-gaging station.

The Whitman & Howard, Inc. (1992) report provided the results of sieve analyses for streambed materials. In general, the samples were taken upstream of the piers at each site. Results from the sieve analyses were checked against records of soil borings included in the bridge design plans for each site.

Establishment of Reference-Point, Reference-Datum and Scour-Reference Surface

For scour measurements made by flood teams, a reference point was established for each site. Measurements to the water surface were made with a steel tape and weight at the beginning and end of each discharge measurement, and at each pier during the discharge measurement. The tape measurements were converted to water-surface elevations based on the datum established at the reference point. Existing cross sections from other studies or bridge design plans were commonly tied to sea level. When readily available, the reference point was tied to sea level. Otherwise, an arbitrary reference datum was established at the site. Individual water-depth measurements were recorded and applied in the computation of the streambed elevations along the upstream and downstream sides of each bridge. The average water-surface elevation during the measurement (average of starting and ending tape measurements) was applied, with the measured water depths at each vertical, to compute streambed elevations.

Scour-reference surfaces were based on adjacent streambed elevations measured beyond scour holes near each pier. Use of adjacent streambed elevations provides an estimate of the pier-scour-depth (local scour) but neglects any contraction-scour that may also be present at a pier. Streambed elevations measured on stone fill or debris were considered part of the pier geometry and were not used to establish the scour-reference surface.

COMPARISON OF SCOUR DATA-COLLECTION METHODS

No single method can be used to measure scour precisely at all bridge sites in New Hampshire. Each method utilized in this study (flood team, ground-penetrating radar, and fixed instrumentation) has advantages and disadvantages. When several methods are used together, the best possible measurements and documentation of scour at any bridge site are attained. This section provides a qualitative assessment of the effectiveness of each technique under conditions observed at selected bridges in New Hampshire during the study period.

Measurements by Field Teams

During a flood, a mobile flood team can be dispatched to a bridge site to obtain valuable scour-measurement and scour-prediction data. Flood-team measurements require personnel with truck-mounted or portable cranes deploying sounding weights and current meters to collect scour-related data.

The ability to make scour measurements in the field depends on several factors, two of which are the location of the physical measurement at the bridge site and the technique used to make the measurement. Cross sections along the upstream and downstream bridge-face can be measured directly from the bridge deck with the measuring equipment suspended over the side of the bridge from a crane.

Where piers are skewed to the flow direction, it can be difficult or impossible to position the sounding weight and current meter alongside and upstream or

Table 3. Drainage areas, flood frequencies, and peak discharges during the study period for watersheds above examined bridge sites in New Hampshire

[DA, Drainage area; Q_x, discharge at recurrence interval (x); NHDOT, New Hampshire Department of Transportation; USGS, U.S. Geological Survey; FEMA, Federal Emergency Management Agency; US, United States Route; N.H., State Route; I, Interstate Route; mi^2, square miles; ft^3/s, cubic feet per second; e, estimated value]

Site No. (fig. 1)	Location	Source of DA and Q_x	Drainage area, (mi^2)	Discharge, in ft^3/s at recurrence interval, in years					April 1996 to November 1998
				Q_2	Q_{10}	Q_{50}	Q_{100}	Q_{500}	Maximum Q, in ft^3/s
1	US 3/N.H. 25 over the Pemigewasset River	NHDOT	634	e 21,400	37,700	54,800	62,800	83,800	e22,500
2	N.H. 104 over the Pemigewasset River	NHDOT	735	e 23,300	40,800	59,600	68,500	91,700	e25,000
3	US 3 over the Connecticut River	USGS	259	2,630	3,780	4,700	5,080	5,940	5,270
4	N.H. 9 over the Soucook River	USGS	76.8	1,320	2,410	4,100	5,050	7,600	2,120
5	N.H. 153 over the Ossipee River	USGS	330	3,530	5,940	8,480	9,720	13,000	7,690
6	N.H. 153 over the Cocheco River	FEMA	33.1	e 1,100	2,320	4,220	5,190	7,990	e1,900
7	US 2 over the Israel River	NHDOT	78	1,970	3,820	6,340	7,680	13,100	e6,400
8	I-93 Northbound Exit Ramp over the Pemigewasset River	NHDOT	22.3	830	1,750	3,200	3,930	6,680	e3,000
9	I-93 Southbound over the Connecticut River	NHDOT	1,600	29,400	34,800	45,300	49,800	60,500	44,300
10	I-93 Northbound over the Connecticut River	NHDOT	1,600	29,400	34,800	45,300	49,800	60,500	44,300
11	N.H. 18 over the Connecticut River	NHDOT	1,600	29,400	34,800	45,300	49,800	60,500	44,300
12	N.H. 13 over the Souhegan River	FEMA	e 150	e 2,700	5,400	9,300	11,100	16,500	e4,900
13	I-93 Southbound over the Winnipesaukee River	USGS	469	2,200	3,400	4,900	5,600	7,600	3,940
14	I-93 Northbound over the Winnipesaukee River	USGS	469	2,200	3,400	4,900	5,600	7,600	3,940
15	N.H. 107 over the Lamprey River	FEMA	33	e 1,200	2,400	3,700	4,200	5,400	2,020
16	N.H. 113 over the Cold River	NHDOT	31	1,500	3,500	6,700	8,400	14,000	4,450
17	N.H. 9 over Otter Brook	NHDOT	35	1,000	2,100	3,500	4,300	7,300	e1,300
18	N.H. 140 over the Winnipesaukee River	USGS	468	2,200	3,400	4,900	5,600	7,600	3,940
19	I-89 Southbound over the Warner River	FEMA	83	e 1,500	3,000	5,100	6,200	9,600	e2,000
20	I-89 Northbound over the Warner River	FEMA	83	e 1,500	3,000	5,100	6,200	9,600	e2,000

downstream from the nose of the pier to obtain an accurate depth/velocity measurement. During floods, current meters and sounding weights are exposed to turbulent flow, bed-material movement, and floating debris. The effects of turbulent flow on soundings can be eliminated by the use of a large sounding weight, greater than 150 lbs (68.9 kg), suspended from the cable below the current meter. Movement of bed materials is variable and unpredictable. Floating debris (commonly logs and trees) is another hazard. Debris may snag the sounding cable, which may require cutting the cable to release the sounding weight and velocity meter. This situation can usually be avoided by constantly scanning the upstream water surface for debris and either steering the equipment away from it or quickly raising the equipment out of the water to allow the debris to pass beneath and through the bridge opening. The personnel-intensive requirements of flood-team measurements limit the number of measurements that can be obtained during widespread flooding. Personnel safety can also be of concern during large flood events.

Ground-Penetrating Radar

Ground-Penetrating Radar is an effective technique for measuring scour before and after a flood, when the water is low, turbulence is minimal, and conditions are less hazardous to personnel. GPR data can be readily collected in any area around the bridge using a portable, inflatable boat as a deployment platform. GPR is also an effective tool to measure scour around the entire perimeter of piers and along the upstream and downstream bridge faces, which is a limitation of flood-team measurements and fixed instruments.

Although GPR provides a potential opportunity for collecting scour data after an event, through the comparison of pre-event and post-event profiles, water depths and streambed conditions must be conducive to the use of this technique. GPR can be used in relatively shallow water of less than 20 ft (6.1 m). In water deeper than this, the signal is attenuated or cut-off, resulting in limited penetration in bed sediments (Gorin and Haeni, 1989). In this study, water depths were less than 20 ft (6.1 m) at all sites and at only 2 sites were water depths greater than 5 ft (1.52 m). GPR was used successfully at the shallow water sites; however, at the deeper water sites with water depths greater than 5 ft (1.52 m), the streambed profile is identified in the record but penetration into the streambed material is limited due to signal loss.

Streambed materials also affected the penetration of the radar signal. Bridge sites that had medium to coarse sand, gravel, and some cobbles proved to be sites in which the radar signal could penetrate the streambed. In this study, 19 of 44 (43 percent) bridge sites had bed materials consisting of sand or sand and gravel with cobbles. The remaining sites had bed materials consisting of large boulders and cobbles with little interstitial sand, or till and boulder channels and were not successfully profiled with GPR. Large boulders, cobbles, and till prevent the radar signal from penetrating the streambed resulting in multiple reflections (interference) being repeated throughout the cross section.

Refilling of scour holes was not as clearly defined in the GPR records as anticipated for the coarse-grained-streambed sites examined in New Hampshire, possibly the result of clear-water conditions with little scour-hole infilling. GPR, however, has proven effective in identifying refilled scour holes in other studies (Placzek and Haeni, 1995).

Fathometer

Fathometer measurements were unsuccessful during the floods measured in New Hampshire. Measurements were difficult to make because (1) shallow streams with high velocities captured air in the water column, which attenuated or shortened the sonar pulse; and (2) the turbulent flow and standing waves in shallow, high velocity, steep-gradient streams caused the knee-board to bounce uncontrollably, capsize, or submerge abruptly.

Fixed Instruments

The use of fixed instruments mounted to bridge piers also is an effective way to measure and monitor scour at bridge sites, but it limits the collection of data to the area directly beneath the instrument. In order to gain a complete understanding of the depth and extent of scour holes that develop at a pier during a flood, depth measurements need to be made at multiple points around the perimeter of a pier. The drawback to this approach is that multiple measurement points require multiple sensors, which are expensive to purchase, install, and maintain.

Many recording instruments are capable of handling multiple sensors and managing the data for up to 16 sonic transducers at a pier. For example, the Datasonics PSA-902 and the Campbell Scientific CR-10 sonar instruments have capacities for up to 16 and 6 sonic transducers, respectively. Acoustic instruments also can be effective for measuring scour and fill during a flood. Mechanical instruments such as sliding rod or sliding collar devices are effective for measuring maximum scour depths.

Fixed instruments are vulnerable to a variety of outside influences that may interrupt or terminate the data-collection process. The physical location of a transducer at the pier nose a few feet above the water surface lends itself to interruptions in sonar readings caused by debris hanging on the transducer, and in winter, by ice tearing the transducer off the pier. In this study, all transducers were installed at bridge sites where debris problems were minimal. The protective mount of each transducer was constructed of 3/16- or 1/4-in-steel sheets, which were bolted to the concrete pier nose. The physical strength of the mount largely eliminated damage to the transducers by debris and ice.

Fixed recording instruments are susceptible to lightning strikes and vandalism. A recording instrument in Littleton was struck by lightning in September 1997, damaging the instrument and rendering the data unrecoverable. In November 1997, and again in December 1998, the solar panels that supplied power at the State Route 18 site in Littleton were stolen. The memory card and voltage controller were destroyed, also rendering the data unrecoverable. In each instance, the instrument had to be removed from the bridge and returned to the manufacturer for electronic repairs.

Low temperatures also are a factor in the automated data-collection process at bridge sites in New Hampshire. Temperatures below 10 degrees Fahrenheit (-12 degrees Celsius) caused battery voltage to drop below levels required to sustain the recording instrument. A heavy blanket of insulation and frequent winter-time site visits insured data recording continued without interruption through the winter.

METHODS OF ANALYSIS OF SCOUR DATA

Observed Pier Scour

For most sites visited by flood teams, no pier-scour was measured. Where multiple measurements were made during a flood, the first soundings were used as the initial condition. Subsequent measurements provided estimates of streambed scour or accretion over time. For estimation of pier scour, a new scour-reference surface was established for each subsequent measurement to isolate the effects of any contraction-scour.

For sites with interpretable GPR record (table 1), the streambed cross section from the 1996 survey was used as the initial condition. Scour surfaces from prior floods were identified in the initial GPR surveys in an effort to document and later distinguish them from new scour surfaces. Differences in the depths from the scour-reference surface at each pier between the 1996 and post-flood GPR survey later in 1998 were computed.

Scour-reference depths at the sonic fixed instruments were those depths recorded prior to the initial increase in recorded depth associated with a scour event. Depths from sonic methods will account for infilling (if any) at the fixed instrument before each scouring event. The sliding rod fixed instrument will not account for fill before new scouring; therefore, the scour-reference depth at the sliding rod instrument was the last depth measurement recorded before a scour event. The maximum depth measured at the fixed instruments was recorded as the pier-scour depth during a scour event.

Selection of Parameters and Variables for Use in Pier-Scour Equations

Basic site characteristics, which are parameters associated with most pier-scour equations, include the shape, length, and width for each pier. These parameters were determined from previous scour analysis (Whitman & Howard, Inc., 1992) and from design plans for each bridge. Ranges in these parameters for the 20 sites investigated are shown in table 2.

Angle-of-attack of the approaching streamflow and the D_{50} of bed material particles were ascertained through the bridge-scour-analyses files from Whitman & Howard, Inc. (1992). Whitman & Howard, Inc. (1992) also provided the results of grain-size analyses of samples of streambed material collected upstream from each site. A graph of the cumulative distributions of streambed material size was available for each site assessed in their report. The median grain size (D_{50}), and any other particle sizes required, were derived from graphs in that report. Although angle-of-attack and the D_{50} of the bed material may vary somewhat during and between floods, these characteristics were assumed to be constant.

Water temperatures used in bridge-scour equations were assumed to be the instantaneous temperatures measured at streamflow-gaging stations on a nearby river or the river of interest at the time of the scour measurement. Where a water-temperature measurement was not made, the minimum air temperature for the day of the scour measurements, or on the day of the estimated maximum discharge (assumed scour event), was used to represent the water temperature. Air temperatures were obtained from monthly climatic data summaries (National Oceanic and Atmospheric Administration, 1996 and 1998) for nearby weather stations. Temperature is used to estimate the density and dynamic viscosity of water in the computations of pier scour for some equations. Temperature, however, had no significant effect on the scour predicted for the sites examined.

Variables common to pier-scour computations are the depth and velocity of streamflow immediately upstream of a pier. At sites where measurements were made by flood teams, values for depth and velocity were obtained immediately upstream of the nose of a pier. These are listed by site and by the date of the measurement in table 2. When multiple measurements of velocity and depth at the pier were made, the average of the velocities was computed and applied in the pier-scour equations. Where no measurement date is provided in table 2, the discharge is an estimate of the maximum discharge over the period April 1996 through November 1998, based on records from nearby streamflow-gaging stations. Observed scour depths in table 2 from GPR surveys and fixed instruments were assumed to be associated with the maximum discharge event between measurements. Estimates of depth and velocity immediately upstream of each pier for GPR or fixed instrument sites, at the estimated maximum discharge for the scour event, were based on interpolation and extrapolation of hydraulic variables obtained from existing one-dimensional step-backwater models (Whitman & Howard, Inc., 1992) for each site.

Equations Used to Compute Pier-Scour Depths

Equations from the most recent edition of Hydraulic Engineering Circular No. 18 (HEC-18) by Richardson and Davis (1995), and from Landers and Mueller (1996), and Mueller (1996) were incorporated in a computer program called the Bridge Scour Evaluator (BSE), version 6 (David Mueller, U.S. Geological Survey, written commun., February 1999). Although BSE includes computations for contraction, abutment, and pier scour, only the pier-scour computations section was used for the computations in this study. The Jain-Fischer (Jain and Fischer, 1979) and the New York 1996 (Gerald Butch, written commun., 1998) equations were incorporated into a spreadsheet for pier-scour depth computations.

The original edition of HEC-18 (Richardson and others, 1991) documented an equation for predicting pier-scour depths. The equation was developed at Colorado State University (CSU) and described in Richardson and others (1990) for computing equilibrium pier-scour depths, and was recommended for pier-scour predictions under live-bed and clear-water flow conditions. The CSU equation was modified with the addition of the K_3 and K_4 coefficients in equation 1 below and was documented in later revisions of HEC-18 (1995). The first revision included the K_3 coefficient for modifying pier-scour depths from equilibrium to maximum depths expected by adjusting for the potential effects of bed forms, such as dunes (Richardson and others, 1993). The latest revision of HEC-18 included an additional coefficient, K_4, in the pier-scour equation to correct maximum scour depths for the effects of large-size bed material armoring the scour hole (Richardson and Davis, 1995). This latest edition of the Federal Highway Administration’s recommended pier-scour equation applied in this analysis is

$$y_{sp} = 2.0 y_0 K_1 K_2 K_3 K_4 \left(\frac{b}{y_0}\right)^{0.65} F_0^{\ 0.43} \quad , \qquad (1)$$

where

y_{sp} is the depth of pier scour below the ambient bed elevation (m);

y_0 is the depth of flow immediately upstream of the pier (m);

K_1 is a coefficient based on the shape of the pier nose (table 4);

K_2 is a coefficient based on the angle of attack of the approaching flow and the ratio of the pier length to the pier width, L/b, (table 5);

K_3 is a coefficient based on the bed condition (table 6);

K_4 is a coefficient to correct for armoring by large particles in the bed material;

L is the pier length (m);

b is the pier width (m); and

F_0 is the Froude number for the flow immediately upstream of the pier.

The Froude number, F_0, in equation 1 is computed by use of the following equation

$$F_0 = \frac{V_0}{\sqrt{gy_0}}, \tag{2}$$

where

V_0 is the flow velocity immediately upstream of the pier (m/s), and

g is the acceleration due to gravity (9.81 m/s^2).

The K_4 factor is computed by

$$K_4 = \sqrt{1 - 0.89(1 - V_R)^2}, \tag{3}$$

where

V_R is a dimensionless velocity ratio computed by

$$V_R = \left(\frac{V_0 - V_i}{V_{c(D_{90})} - V_i}\right), \tag{4}$$

Table 4. Correction factor (K_1) for the shape of the pier nose

[From Richardson and Davis, 1995]

Shape of pier nose	K_1
Square	1.1
Round	1.0
Circular cylinder	1.0
Group of cylinders	1.0
Sharp nose	0.9

Table 5. Correction factor (K_2) for angle of attack of approaching flow and the ratio of pier length to pier width

[From Richardson and Davis, 1995; L, pier length; b, pier width]

Angle of attack	Ratio of pier length to pier width		
	L/b = 4	L/b = 8	L/b = 12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.75	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

Table 6. Correction factor (K_3) for streambed condition

[From Richardson and Davis, 1995; --, not applicable; >, greater than; H, height]

Streambed condition	Dune height, in meters	K_3
None, clear-water scour	--	1.1
Plane bed and antidunes	--	1.1
Small dunes	3 > H > 0.6	1.1
Medium dunes	9 > H > 3	1.1 to 1.2
Large dunes	H > 9	1.3

where

V_i is the incipient-motion velocity for bed material particles at the pier computed by

$$V_i = 0.645\left(\frac{D_{50}}{b}\right)^{0.053} V_{c(D_{50})}, \tag{5}$$

where

D_{50} is the median diameter of bed material particles (mm), and

$V_{c(D_n)}$ is the critical velocity for the D_n particle diameter, in meters, for which n percent of the particle diameters are smaller and is computed by use of

$$V_{c(D_n)} = 6.19 y_0^{1/6} D_n^{1/3}, \qquad (6)$$

where

y_o is the depth of flow immediately upstream of the pier, in meters; and

D_n is the median diameter of bed material particles, in millimeters.

When angles of attack were less than 5 degrees, K_2 was set to 1.0 as recommended in HEC-18 (Richardson and Davis, 1995). For this study, the K_3 coefficient was set to 1.1 for all pier-scour computations with the HEC-18 equation. The K_4 coefficient is applicable when the median bed material size (D_{50}) is greater than or equal to 0.20 ft (0.06 m) and has a minimum value of 0.7 and a maximum value of 1.0 for V_R values greater than or equal to 1.0 from equation 3.

For cases in which pier footings are exposed by general or contraction scour, HEC-18 (Richardson and Davis, 1995) provides computations for adjusting the velocity of flow immediately upstream of the pier to the velocity of flow below the top of the pier footing, and provides procedures for computing the scour depth. Scour between 1996 and 1998 was observed at only site 1 along an exposed footing. For this site, the velocity adjustment and technique described in HEC-18 (Richardson and Davis, 1995) were used with each equation to compute and select pier-scour depths.

Gao and others (1993), as discussed in Landers and Mueller (1996), provided a live-bed and clear-water pier scour equation (the Simplified Chinese equation, table 7). Incipient-motion analyses involved in these computations indicated the velocities were insufficient to move the D_{50}-size particle at each pier examined, as V_c was greater than V_c'. Thus, the Simplified Chinese equation for clear-water scour conditions was applied.

Most of the pier-scour depth equations used in this study were selected from the set of equations reviewed and compiled by Landers and Mueller (1996) and Mueller (1996). The selected equations are combined and listed by equation name in table 7. Equations selected for computing pier-scour depths and listed in table 7, which were not included in Landers and Mueller (1996), were those developed and documented by Melville and Sutherland (1988), Jain and Fischer (1979), and Gerald Butch (written commun., 1998). These equations are provided and briefly described below.

The equation published by Melville and Sutherland (1988) in Mueller (1996) is used for bridge design purposes and is based on several laboratory experiments by Melville (1975), Ettema (1976, 1980), Chee (1982), Chiew (1984) and Baker (1986) in New Zealand. Melville and Sutherland (1988) surmised that the maximum depth of pier scour expected is 2.4 times the pier width for piers that are aligned with the flow. The maximum depth of pier scour is then reduced by the effects of flow intensity, flow depth, bed material, pier shape, and angle of attack. The equation is

$$y_{sp} = K_I K_d K_y K_1 K_2, \qquad (7)$$

where

K_I is a coefficient for flow intensity,

K_d is a coefficient for sediment size, and

K_y is a coefficient for the flow depth.

K_I is defined by

$$K_I = 2.4\left|\frac{V_0 - (V_a - V_c)}{V_c}\right| \quad \text{when}$$

$$\frac{V_0 - (V_a - V_c)}{V_c} < 1.0 \text{ , and}$$

$$K_I = 2.4 \quad \text{when} \quad \frac{V_0 - (V_a - V_c)}{V_c} > 1.0 \text{ .}$$

V_c is defined by

$$V_c = 5.75 u_{*c} \log\left(5.53 \frac{y_0}{D_{50}}\right), \qquad (8)$$

where

u_{*c} is the critical shear velocity, in meters per second, from Shields diagram (fig. 3) for a D_{50}, which is less than 60 mm. Otherwise, the critical shear velocity is computed as $0.03\sqrt{D_{50}}$; and

Table 7. Equations reviewed and used for pier-scour computations

[Definition of variables for equation HEC-18, CSU, and Simplified Chinese are used for other equations listed in this table]

Equation name and reference(s)	Equation	Variables, units, and other notes
HEC-18 Richardson and Davis (1995)	$y_{sp} = 2.0 y_0 K_1 K_2 K_3 K_4 \left(\frac{b}{y_0}\right)^{0.65} F_0^{0.43}$ where $K_4 = \sqrt{1 - 0.89(1 - V_R)^2}$ $V_R = \left(\frac{V_0 - V_i}{V_{c(D90)} - V_i}\right)$ $V_i = 0.645 \left(\frac{D_{50}}{b}\right)^{0.053} V_{c(D50)}$ and $F_0 = \frac{V_0}{\sqrt{g y_0}}$	NOTE: The HEC-18 equation is not dimensionless; y_{sp} is the depth of pier scour below the ambient bed elevation, in meters. y_0 is the depth of flow immediately upstream of the pier, in meters. K_1 is a coefficient based on the shape of the pier nose (table 4). K_2 is a coefficient based on the angle of attack of the approaching flow and the ratio of the pier length to the pier width, *L/b*, (table 5). *L* is the pier length, in meters. *b* is the pier width, in meters. K_3 is a coefficient based on the bed condition (table 6). K_4 is a coefficient to correct for armoring by large particles in the bed material. V_R is a dimensionless velocity ratio. V_i is the incipient-motion velocity for bed material particles at the pier, in meters per second. D_{50} is the median diameter of bed material particles, in millimeters. $Vc(D_n)$ is the critical velocity for the D_n particle diameter, in meters, for which *n* percent of the particle diameters are smaller. F_0 is the Froude number for the flow immediately upstream of the pier. V_0 is the flow velocity immediately upstream of the pier, in meters per second. *g* is the acceleration due to gravity (9.81 meters per second squared).
CSU Richardson and others (1990)	$y_{sp} = 2.0 y_0 K_1 K_2 \left(\frac{b}{y_0}\right)^{0.65} F_0^{0.43}$	NOTE: The CSU equation is not dimensionless; Same as HEC-18 equation without K_3 and K_4 coefficients.

Table 7. Equations reviewed and used for pier-scour computations—Continued

Equation name and reference(s)	Equation	Variables, units, and other notes
Ahmad Ahmad (1953)	$y_{sp} = KV_0^{2/3} y_0^{2/3} - y_0$	NOTE: The Ahmad equation is not dimensionless. y_{sp} and y_0 are in feet, and V_0 is in foot per second. K is a factor, which is a function of the boundary geometry, pier width, pier shape, and angle of the approach flow. Whereas recommended K values range from 1.7 to 2.0, it was assumed to be 1.8 for pier-scour computations in this study.
Blench - Inglis II Blench (1951, 1962, 1969) and Inglis (1949)	$y_{sp} = 1.53 b^{0.25} V_0^{0.5} y_0^{0.5} D_{50}^{-0.125} - y_0$	NOTE: The Blench-Inglis II equation is not dimensionless; as b, y_{sp} and y_0 are in feet, V_0 is in foot per second and D_{50} is in millimeters.
Simplified Chinese Gao and others (1993)	$y_{sp} = 0.78 K_s b^{0.6} y_0^{0.15} D_m^{-0.07} \left(\frac{V_0 - V_c'}{V_{c(Dm)} - V_c'}\right)^c$ where $V_{c(Dm)} = \left(\frac{y_0}{D_m}\right)^{0.14} \sqrt{17.6\left(\frac{r_s - r}{r}\right) D_m + 6.05X10^{-7}\left(\frac{10 + y_0}{D_m^{0.72}}\right)}$ and $V_c' = 0.645\left(\frac{D_m}{b}\right)^{0.053} V_{c(Dm)}$	NOTE: The Simplified Chinese equation is not dimensionless; The variables y_{sp}, y_0, b, and D_m are in meters, V_c is in meters per second, and c is 1.0 for all piers examined (clear-water scour). Ks is a simplified pier shape coefficient defined as 1.0 for cylinders, 0.8 for round nosed, and 0.66 for sharp-nosed piers. Dm is the mean particle diameter of the bed material. The median diameter particle size was used as a proxy for the mean for all computations. $V_{c(Dm)}$ is the critical velocity for the mean diameter-size particle. V_c' is the approach velocity accociated with the critical velocity and incipient scour in the accelerated flow region at the pier. ρ_s is the density of sediment assumed to be 2.65 for all computations. ρ is the density of water.

Table 7. Equations reviewed and used for pier-scour computations—Continued

Equation name and reference(s)	Equation	Variables, units, and other notes
Melville-Sutherland Melville and Sutherland (1988)	$y_{sp} = K_I K_d K_y K_1 K_2 b$ where $K_I = 2.4\left\lvert\frac{V_0 - (V_a - V_c)}{V_c}\right\rvert$ when $\frac{V_0 - (V_a - V_c)}{V_c} < 1.0$ $K_I = 2.4$ when $\frac{V_0 - (V_a - V_c)}{V_c} > 1.0$ $V_c = 5.75 u_{*c} \log\left(5.53 \frac{y_0}{D_{50}}\right)$ $V_a = 0.8V_{ca}$ when $V_a > V_c$, otherwise $V_a = V_c$ $K_d = 1.0$ when $b/D_{50} > 25.0$ and $K_d = 0.57 \log(2.24\ b/D_{50})$ when $b/D_{50} < 25.0$ $K_y = 1.0$ when $y_0/b > 2.6$ and $K_y = 0.78\ (y_0/b)^{0.255}$ when $y_0/b < 2.6$	K_I is a coefficient for flow intensity. u_{*c} is the critical shear velocity in meter per second from Shields diagram in figure 4 for a D_{50}, which is less than 60 millimeters. Otherwise, the critical shear velocity is computed as $0.03\sqrt{D_{50}}$. V_a is the critical velocity of the armor layer. V_{ca} is the critical velocity for the median diameter particle of the armor layer material, D_{50a}, which is computed by replacing the D_{50} with the D_{50a} in the equation for V_c. D_{50a} is defined as $0.556\sigma^{1.65}D_{50}$ where σ is the standard deviation of the bed material. K_d is a coefficient for sediment size. K_y is a coefficient for the flow depth.
Shen Shen and others (1969)	$y_{sp} = 0.00073\boldsymbol{R}_p^{0.619}$	$\boldsymbol{R}_p$ is the pier Reynolds number defined as $\frac{V_0 b}{\nu}$, where ν is the kinematic viscosity of water.
Shen-Maza Maza and Sanches (1964), and Shen and others (1969)	$y_{sp} = 11.0b\boldsymbol{F}_p^2$ for $F_p < 0.2$ $y_{sp} = 3.4b\boldsymbol{F}_p^{0.67}$ for $F_p > 0.2$	Fp is the pier Froude number defined as $\frac{V_0}{\sqrt{gb}}$.

Table 7. Equations reviewed and used for pier-scour computations—Continued

Equation name and reference(s)	Equation	Variables, units, and other notes
Jain-Fischer Jain and Fischer (1979)	For live-bed-scour conditions [for example, $(F_0 - F_c) > 0.2$]: $y_{sp} = 2.0b(F_0 - F_c)^{0.25}\sqrt{\frac{y_0}{b}}$ and for maximum clear-water scour conditions: $y_{sp} = 1.84bF_c^{0.25}\left(\frac{y_0}{b}\right)^{0.3}$ where $F_c = V_c / \sqrt{gy_0}$ $V_c = 2.5u_{*c}\ln\left(11\frac{Xy_0}{D_{50}}\right)$ and $u_{*c} = \sqrt{\tau_c / \rho}$	NOTE: The Jain-Fischer equation is not dimensionless; *b* is the pier width, in meters; Y_o is the depth of flow immediately upstream of the pier, in meters; D_{50} is the median diameter of bed material particles, in millimeters. *Fc* is the critical Froude number at the threshold of bed material motion. *X* is Einstein's Factor obtained from Richardson and others (1990, fig. 2.3.5, p. II-24). τ_c is the critical tractive force for the D_{50} size particle obtained by use of Lane's diagram from Richardson and others (1990, figure 3.5.2, p. III-41).
New York 1996 Welch and Butch, U.S. Geological Survey, written commun., 1999)	$y_{sp} = 6.21 \times 10^{-7}\frac{p}{D_{84}} - 0.07$ where $p = \rho y_0 w V_0^2$	NOTE: The New York 1996 equation is not dimensionless; *p* is the local momentum of a 1-meter-wide column of water immediately upstream of a pier. D_{84} is the diameter of the particle for which 84 percent of the bed material particles are smaller than D_{84}, in meters. *w* is assumed to be 1.0 meter. ρ is assumed to be 1,000 kilograms per cubic meter. Y_{sp} is in meters.

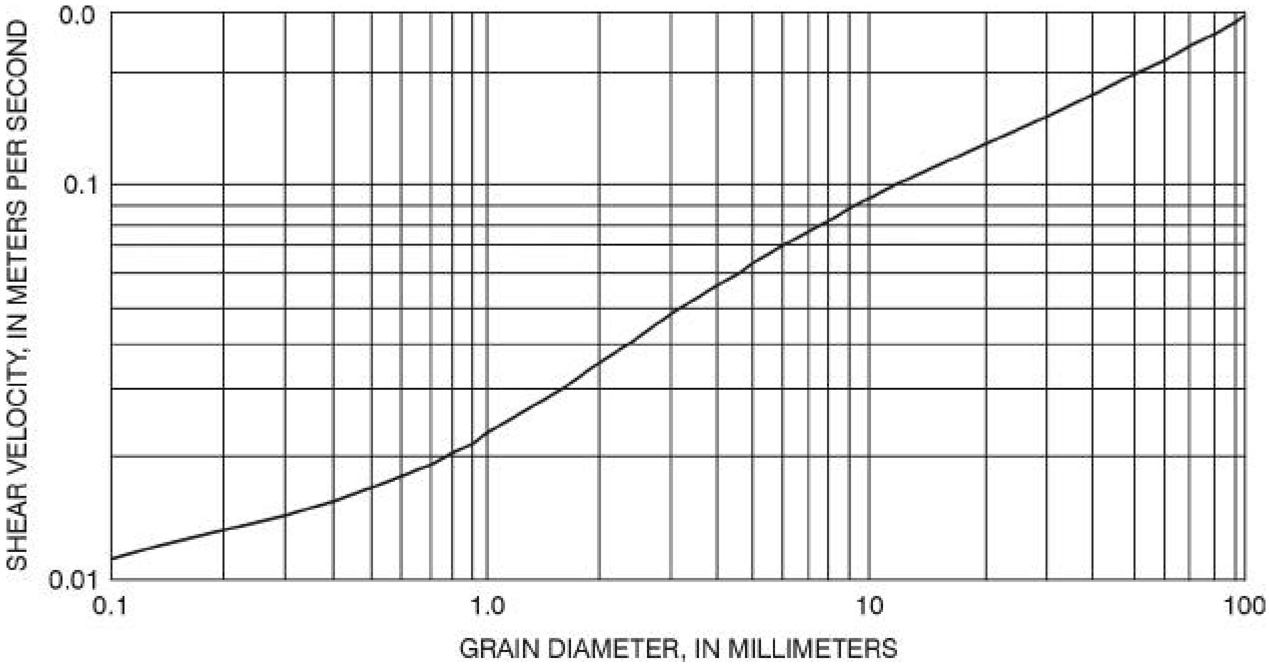

Figure 3. Shields diagram for threshold condition of uniform sediments in water (from Melville and Sutherland, 1988).

V_a is the critical velocity of the armor layer, which is defined as

$V_a = 0.8V_{ca}$ for $V_a > V_c$, otherwise $V_a = V_c$,

where

V_{ca} is the critical velocity for the median diameter particle of the armor layer material; D_{50a}, which is computed by use of equation 8 replacing the D_{50} with the D_{50a}. The D_{50a} is defined as $0.556\sigma^{1.65}D_{50}$; where σ is the standard deviation of the streambed material;

K_d is 1.0 when $b/D_{50} > 25.0$ and $0.57 \log(2.24\, b/D_{50})$ when $b/D_{50} < 25.0$; and

K_y is 1.0 when $y_0/b > 2.6$ and $0.78\,(y_0/b)^{0.255}$ when $y_0/b < 2.6$.

Richardson and others (1990) briefly describe the pier-scour equations developed by Jain and Fischer (1979) for live-bed and clear-water conditions. Jain and Fischer (1979) studied the local scour process at high flow velocities (high Froude numbers) and found that the depth of pier scour initially decreases under live-bed conditions before increasing as Froude numbers increase. The maximum scour under clear-water conditions is large at high Froude numbers.

From their laboratory experiments, the following equations were generated

$$y_{sp} = 2.0b(F_0 - F_c)^{0.25}\sqrt{\frac{y_0}{b}}\ , \qquad (9)$$

where

b is pier width, in meters; and

Y_o is depth of flow immediately upstream of the pier, in meters.

For live-bed defined by $(F_0 - F_c) > 0.2$, and for maximum clear-water scour

$$y_{sp} = 1.84bF_c^{0.25}\left(\frac{y_0}{b}\right)^{0.3}\ , \qquad (10)$$

where

F_c is the critical Froude number at the threshold of bed material motion defined as

$$F_c = V_c/\sqrt{gy_0}\ .$$

The critical velocity, V_c, is computed by

$$V_c = 2.5 u_{*c} \ln\left(11 \frac{X y_0}{D_{50}}\right) , \qquad (11)$$

where

V_c is the critical velocity, in meters, and

X is Einstein's Factor obtained from Richardson and others (1990, fig. 2.3.5, p. II-24).

Einstein's Factor was 1.0 for most of the pier-scour computations in this study. The critical shear velocity for use in equation 8 was computed by $u_{*c} = \sqrt{\tau_c / \rho}$, where τ_c is the critical tractive force for the D_{50} size particle obtained by use of Lane's diagram from Richardson and others (1990, fig. 3.5.2, p. III-41).

Gerald Butch (written commun., 1998), developed a pier-scour equation based on 61 discrete scour measurements from 1988 through 1996 at 20 sites in New York State. Discrete scour measurements were considered depths of scour associated with a specific peak discharge. The New York 1996 equation is based on the ratio of the local momentum (p) of a meter-wide column of water at the pier to the D_{84}-size particle of the bed material at the pier (p/D_{84}). Local momentum is defined as

$$p = \rho y_0 w V_0^2 , \qquad (12)$$

where

w is the flow width, in meters; and

ρ is the density of water, in kilograms per cubic meter.

Measurements of velocity and depth at the pier were assumed to apply over a 1-meter wide column of water for the purpose of consistently computing the momentum. The density of water was assumed to be 1,000 kg/m^3 (62.6 lb/ft^3). A simple linear regression analysis was conducted between the p/D_{84} ratio and discrete scour depth, which resulted in the New York 1996 equation:

$$y_{sp} = 6.21 \times 10^{-7} \frac{p}{D_{84}} - 0.07 \ . \qquad (13)$$

The regression included 18 measurements of zero scour depth, which influence variance below p/D_{84} ratios of 10^5 kg/s^2. The equation represents discrete pier-scour depths measuring up to 4.92 ft (1.5 m).

RESULTS AND COMPARISON OF MEASURED AND PREDICTED SCOUR

Measured Pier Scour

Depths of pier scour measured by flood teams, from GPR survey data, and by fixed-instruments are presented in table 2. Measurements by flood teams indicated pier scour at only one site. Cross sections measured by the flood team indicated scour at piers 2 and 3 between the first and second measurements made on April 2, 1998, at the bridge on State Route 18 across the Connecticut River in Littleton (site 11). The scour appeared at the contact with stone fill, which encompasses both piers, and the adjacent streambed, primarily on the right sides of the piers. Scour depth at each pier was 0.7 ft (0.21 m).

Pier scour was indicated in the GPR records for five sites. The flood team made measurements at three of these sites (4, 11, 16, table 1) but detected scour only at site 11. Streambed measurements made by soundings were restricted to the downstream and upstream sides and the ends of each pier, but GPR records showed scour underneath the bridge along the side of a pier and further upstream from the nose of the pier. For site 11, the GPR images show scour at the contact of the stone fill and streambed material upstream of the nose of piers 2 and 3. GPR revealed larger scour depths at this site than those measured by flood teams. Scour at site 16 was not measured by flood teams, as the first discharge measurement was the highest discharge. The GPR images, however, showed an infilled scour hole at the pier, which meant that the scour depth probably had reached its maximum before, or at the time of, the first measurements at the pier. Images from the GPR surveys for site 4 revealed scour at pier 2 at the second column under the bridge from the upstream side. This scour occurred under the bridge, and the flood team could not measure this scour because of limitations of their equipment.

Two of the four fixed instruments recorded a significant change in depth since installation. The transducer mounted on pier 2 at the State Route 18 site (11) in Littleton recorded an increase in depth of 0.3 ft (0.10 m) in the flood of April 2, 1998. This change in depth was a measurement of a stone-fill slump from the nose of the pier rather than streambed scour, which GPR records showed to be greater at the nose. Therefore, this fixed instrument record was not used to compare with scour prediction equations for this site. Pier scour also was recorded at the US Route 3 bridge, which crosses the Connecticut River in Clarksville (site 3). During the day on April 1, 1998, the scour depth recorded at the bridge was 0.7 ft (0.21 m). The remaining records from fixed instruments showed no significant change in depth from October 1996 through November 1998.

Estimated Pier Scour by Selected Equations

Results of the application of selected pier-scour equations are examined and presented in this section by use of residuals. Residuals are the computed differences between measured scour depths and equation-predicted scour depths at each pier (table 8). Positive residuals indicate that the equations underpredicted scour, and negative residuals indicate overprediction of scour. The closer the residual depths are to zero without underpredicting scour, the more reliable the equation is considered to be.

Results are presented in two groups. The first group includes residuals based on scour, velocity, depth and discharge measurements by flood teams for sites 4, 5, 11, 15, and 16 (table 8). The second group includes residuals based on the scour measured by GPR and fixed-instruments and estimated depth and velocities for the scour event (table 9). Residuals also are presented graphically (boxplots) to show differences in pier-scour depths computed by the selected equations (figs. 4 and 5). Residuals were negative for sites with no measurable scour, indicating that pier scour is overpredicted by the equations.

In seven of the 10 equations used with measured variables (table 8, fig. 4), there were no underestimates of pier-scour. The Blench-Inglis II equation provided residual scour depths mostly within 5 ft (1.52 m) of zero, with no underestimates. Similarly, the Shen equation provided no underestimates of pier scour, but about one-quarter of the predictions were more than 10 ft greater than the measured depths of scour.

Where the predicted pier-scour depths were based on estimates of flow velocity and depth, (table 9, fig. 5) residuals are similar. The Shen equation continued to provide pier-scour-depth predictions closest to those measured without underestimating scour. Boxplots for the Shen and the HEC-18 equations (figs. 4 and 5) show that residual depths (results greater than the 75th percentile) from the Shen equation are closer to zero than those from the HEC-18 equation. The Blench-Inglis II equation underestimated scour at sites 1, 13, and 14 (table 9) and the Simplified Chinese equation underestimated scour at one site (site 1, table 9). However, these two equations resulted in scour predictions within 5 ft of measured scour at more sites than any of the other equations.

Overall, for the six sites where scour greater than zero was measured (1, 3, 4, 11, 12, and 16), the Shen equation most closely predicted the measured scour depths, without underestimating (tables 8 and 9). The New York 1996, Simplified Chinese, and Blench-Inglis II equations provided predictions of scour depth close to zero, however, pier-scour depth was underestimated by each of these equations at some sites. The New York 1996 equation underestimated scour depths for about 50 percent of the sites. For the six sites where scour was measurable (sites 1, 3, 4, 11, 12, and 16), this equation underestimated scour for five piers at four of the sites (1, 3, 11, and 16) by as much as 2.3 ft (0.70 m). The sites where scour was underestimated were among those with the largest diameter bed material (28 to 80 mm, table 2). For the other two sites (4, 12) where scour was measured, the New York-1996 equation overpredicted the depth of scour by more than 10 ft (3.05 m). These sites had some of the smallest diameter bed material (0.4 to 7 mm, table 3). These results demonstrate the increased sensitivity of the New York equation to decreases in bed-material particle size, as identified by Gerald Butch (written commun., 1998).

The Simplified Chinese equation and Blench-Inglis II equation underestimated scour less than 25 percent of the time. For sites with measurable scour, both equations underestimated scour for pier 7 at site 1 (table 9). The Simplified Chinese and Blench-Inglis II equations underestimated scour by 0.1 ft and 0.3 ft (0.03 m and 0.09 m) respectively, which are at or below the resolution of depth measurements by GPR.

Table 8. Residual depths of pier scour computed by use of each equation for bridge sites examined with flood-team measurements by date in New Hampshire

[ft^3/s, cubic feet per second; ft, foot; m, meters; equations are defined in table 7; negative number indicates overestimated scour depth; number in ( ) is in meters]

Site No. (fig. 1)	Measure-ment date	Discharge, in ft^3/s	Pier No.	Scour depth, in ft (m)	Residual depths of pier-scour, in feet and meters, by equation name									
					HEC-18	CSU	Ahmad	Blench-Inglis II	Simplified Chinese	Melville-Sutherland	Shen	Shen-Maza	Jain-Fischer	New York 1996
4	6/17/1998	2,120	1	0.0	-7.2 (-2.19)	-7.2 (-2.19)	-0.3 (-.09)	-1.9 (-.58)	-6.7 (-2.04)	-15.2 (-4.62)	-3.6 (-1.09)	-0.6 (-.18)	-7.0 (-2.13)	-0.8 (-.24)
			2	.0	-7.7 (-2.34)	-7.7 (-2.34)	-2.0 (-.61)	-3.6 (-1.09)	-8.4 (-2.55)	-15.0 (-4.56)	-4.1 (-1.25)	-.9 (-.27)	-6.6 (-2.01)	-1.0 (-.30)
	6/18/1998	1,240	1	.0	-8.5 (-2.59)	-8.5 (-2.59)	-3.6 (-1.09)	-5.1 (-1.55)	-8.8 (-2.68)	-14.6 (-4.44)	-4.9 (-1.49)	-1.4 (-.43)	-6.5 (-1.98)	-1.7 (-.52)
			2	.0	-5.0 (-1.52)	-5.0 (-1.52)	1.0 (.30)	-.7 (-.21)	-.7 (-.21)	-7.0 (-2.13)	-2.4 (-.73)	-.1 (-.03)	-6.2 (-1.89)	.1 (.03)
5	6/16/1998	6,910	1	.0	-8.8 (-2.68)	-8.8 (-2.68)	-7.4 (-2.25)	-.6 (-.18)	.4 (.12)	-3.2 (-.97)	-5.7 (-1.73)	-3.6 (-1.09)	-7.0 (-2.13)	0.2 (.06)
			2	.0	-11.9 (-3.62)	-11.9 (-3.62)	-16.0 (-4.87)	-3.6 (-1.09)	-1.4 (-.43)	-6.2 (-1.89)	-8.7 (-2.65)	-15.2 (-4.62)	-12.7 (-3.86)	.0 (.0)
	6/17/1998	7,690	1	.0	-9.7 (-2.95)	-9.7 (-2.95)	-9.8 (-2.98)	-1.3 (-.40)	.0 (.0)	-3.9 (-1.19)	-6.5 (-1.98)	-11.1 (-3.38)	-7.0 (-2.13)	.2 (.06)
			2	.0	-12.1 (-3.68)	-12.1 (-3.68)	-17.0 (-5.17)	-3.3 (-1.00)	-1.4 (-.43)	-6.1 (-1.86)	-8.7 (-2.65)	-15.2 (-4.62)	-13.3 (-4.05)	.0 (.0)
	6/18/1998	6,850	1	.0	-9.2 (-2.80)	-9.2 (-2.80)	-8.3 (-2.52)	-1.0 (-.30)	.2 (.06)	-3.5 (-1.06)	-6.1 (-1.86)	-10.3 (-3.13)	-7.0 (-2.13)	.2 (.06)
			2	.0	-11.9 (-3.62)	-11.9 (-3.62)	-16.2 (-4.93)	-3.5 (-1.06)	-1.4 (-.43)	-6.2 (-1.89)	-8.7 (-2.65)	-15.2 (-4.62)	-12.9 (-3.92)	.0 (.0)

Table 8. Residual depths of pier scour computed by use of each equation for bridge sites examined with flood-team measurements by date in New Hampshire—Continued

Site No. (fig. 1)	Measure-ment date	Discharge, in ft^3/s	Pier No.	Scour depth, in ft (m)	Residual depths of pier-scour, in feet and meters, by equation name									
					HEC-18	CSU	Ahmad	Blench-Inglis II	Simplified Chinese	Melville-Sutherland	Shen	Shen-Maza	Jain-Fischer	New York 1996
5	6/19/1998	5,960	1	.0	-9.0 (-2.74)	-9.0 (-2.74)	-7.9 (-2.40)	-1.1 (-.33)	0.2 (.06)	-3.5 (-1.06)	-6.0 (-1.82)	-10.1 (-3.07)	-6.9 (-2.10)	0.2 (.06)
			2	.0	-11.1 (-3.38)	-11.1 (-3.38)	-13.4 (-4.08)	-3.0 (-.91)	-1.0 (-.30)	-5.5 (-1.67)	-8.0 (-2.43)	-13.9 (-4.23)	-11.7 (-3.56)	.1 (.03)
11	4/2/1998	44,300	2	.7 (.21)	-14.7 (-4.47)	-14.7 (-4.47)	-29.3 (-8.91)	-5.0 (-1.52)	-3.7 (-1.13)	-17.8 (-5.41)	-12.7 (-3.86)	-28.9 (-8.79)	-30.2 (-9.18)	.3 (.09)
			3	.7 (.21)	-14.7 (-4.47)	-14.7 (-4.47)	-23.9 (-7.27)	-4.7 (-1.43)	-2.8 (-.85)	-15.7 (-4.77)	-11.8 (-3.59)	-26.9 (-8.18)	-27.3 (-8.30)	.5 (.15)
	4/3/1998	33,800	2	.0	-14.5 (-4.41)	-15.4 (-4.68)	-24.0 (-7.30)	-2.1 (-.64)	-1.9 (-.58)	-7.4 (-2.25)	-11.2 (-3.41)	-24.5 (-7.45)	-16 (-4.87)	-.2 (-.06)
			3	.0	-13.8 (-4.20)	-15.4 (-4.68)	-20.8 (-6.33)	-3.4 (-1.03)	-1.8 (-.55)	-13.5 (-4.11)	-11.0 (-3.35)	-24.1 (-7.33)	-15.2 (-4.62)	-.1 (-.03)
15	10/21/1996	1,560	1	.0	-4.9 (-1.49)	-7.0 (-2.13)	-13.4 (-4.08)	-2.4 (-.73)	-1.1 (-.33)	-4.2 (-1.28)	-5.9 (-1.79)	-11.2 (-3.41)	-8.8 (-2.68)	0.1 (.03)
	10/21/1996	2,020	1	.0	-5.1 (-1.55)	-7.3 (-2.22)	-15.1 (-4.59)	-2.6 (-.79)	-1.4 (-.43)	-4.6 (-1.40)	-6.3 (-1.92)	-11.9 (-3.62)	-9.2 (-2.80)	0.1 (.03)
	10/23/1996	1,620	1	.0	-4.8 (-1.46)	-6.8 (-2.07)	-12.8 (-3.89)	-2.3 (-.70)	-1.0 (-.30)	-4.0 (-1.22)	-5.8 (-1.76)	-10.9 (-3.32)	-8.7 (-2.65)	0.1 (.03)
	10/24/1996	804	1	.0	-4.6 (-1.40)	-6.6 (-2.01)	-10.6 (-3.22)	-2.9 (-.88)	-1.3 (-.40)	-4.1 (-1.25)	-6 (-1.82)	-11.3 (-3.44)	-6.9 (-2.10)	.2 (.06)

Table 8. Residual depths of pier scour computed by use of each equation for bridge sites examined with flood-team measurements by date in New Hampshire —Continued

Site No. (fig. 1)	Measure-ment date	Discharge, in ft^3/s	Pier No.	Scour depth, in ft (m)	Residual depths of pier-scour, in feet and meters, by equation name									
					HEC-18	CSU	Ahmad	Blench-Inglis II	Simplified Chinese	Melville-Sutherland	Shen	Shen-Maza	Jain-Fischer	New York 1996
16	6/14/1998	3,790	1	0.0	-7.2 (-2.19)	-7.2 (-2.19)	-14.8 (-4.50)	-2.3 (-.70)	-1.8 (-.55)	-2.4 (-.73)	-6.2 (-1.89)	-10.6 (-3.22)	-8.2 (-2.49)	0.0 (0.0)
	6/15/1998	1,230	1	0.0	-5.0 (-1.52)	-5.0 (-1.52)	-5.5 (-1.67)	-0.9 (-.27)	0.2 (.06)	-2.8 (-.85)	-4.0 (-1.22)	-6.6 (-2.01)	-4.4 (-1.34)	0.2 (.06)
Category					**No. of occurrences in each category of 22 observations by equation**									
Median					-8.9 (-2.71)	-8.9 (-2.71)	-11.7 (-3.57)	-2.8 (-.85)	-1.4 (-.43)	-6.2 (-1.89)	-6.2 (-1.89)	-10.9 (-3.32)	-8.2 (-2.5)	.1 (.03)
Interquartile range					-7.2 to -11.3 (-2.19 to -3.63)	-7.3 to -11.9 (-2.22 to -3.63)	-6.7 to -16.2 (-2.04 to -4.94)	-1.9 to -3.6 (-.58 to -1.10)	-1.0 to -2.8 (-.30 to -.85)	-4.0 to -14.5 (-1.22 to -4.42)	-5.2 to -8.7 (-1.58 to -2.65)	-3.6 to -15.2 (-1.10 to -4.63)	-6.9 to -13.3 (-2.10 to -4.05)	.2 to -.2 (.06 to -.06)
Differences less than -10 ft (-3.05 m)					8	8	13	0	0	6	4	16	8	0
Differences from -5 to -10 ft (0 to -3.05 m)					11	14	5	2	3	6	13	1	13	0
Differences from 0 to -5 ft (0 to -1.52 m)					3	0	3	20	15	10	5	5	1	9
Differences greater than 0 ft (underestimates)					0	0	1	0	4	0	0	0	0	13

Table 9. Residual depths of pier scour computed by use of each equation for bridge sites examined with Ground-Penetrating Radar and fixed instruments in New Hampshire

[ft^3/s, cubic feet per second; ft, foot; m, meter; GPR, Ground-Penetrating Radar; FI, Fixed Instrument; e, estimated; equations are defined in table 7; negative number indicates overestimated scour depth; number in ( ) is in meters]

Site No. (fig. 1)	Discharge, in ft^3/s	Pier No.	Scour depth, in ft (m)	Residual depths of pier scour, in feet and meters, by equation name									
				HEC-18	CSU	Ahmad	Blench-Inglis II	Simplified Chinese	Melville-Sutherland	Shen	Shen-Maza	Jain-Fischer	New York 1996
1	e22,500	7	2.3 (0.70)	-13.9 (-4.24)	-13.9 (-4.24)	-16.4 (-5.00)	0.3 (0.09)	0.1 (.03)	-8.1 (-1.62)	-8.8 (-2.68)	-15.5 (-4.72)	-11.5 (-3.51)	2.25 (0.69)
2	e25,000	1	.0	-7.4 (-2.26)	-7.4 (-2.26)	-2.6 (-0.79)	-8.8 (-2.68)	-6.5 (-1.98)	-14.4 (-4.39)	-4.1 (-1.25)	-2.5 (-.76)	-6.3 (-1.92)	-.5 (-.15)
		2	.0	-9.0 (-2.74)	-9.0 (-2.74)	-16.7 (-5.09)	.0 (.0)	-5.9 (-1.80)	.0 (.0)	-5.6 (-1.71)	-9.4 (-2.87)	-6.1 (-1.86)	-1.6 (-.49)
3	5,270	1	.0	-13.1 (-3.99)	-13.1 (-3.99)	-21.4 (-6.52)	-8.4 (-2.56)	-2.5 (-.76)	-12.3 (-3.75)	-11 (-3.35)	-24.2 (-7.38)	-12.6 (-3.84)	-.6 (-.18)
		1	.7 (.21)	-12.4 (-3.78)	-12.4 (-3.78)	-20.7 (-6.31)	-7.7 (-2.35)	-1.8 (-.55)	-11.6 (-3.54)	-10.3 (-3.14)	-23.5 (-7.16)	-11.9 (-3.63)	.1 (.03)
4	2,120	1	.0	-12.0 (-3.66)	-12.0 (-3.66)	-10.6 (-3.23)	-9.6 (-2.93)	-8.9 (-2.71)	-16.8 (-5.12)	-7.2 (-2.19)	-12.4 (-3.78)	-7.2 (-2.19)	-11.1 (-3.38)
		2	1.1 (.34)	-10.9 (-3.32)	-10.9 (-3.32)	-9.5 (-2.90)	-8.5 (-2.59)	-7.8 (-2.38)	-15.7 (-4.78)	-6.1 (-1.86)	-11.3 (-3.44)	-6.1 (-1.86)	-10.0 (-3.05)
5	7,690	1	.0 GPR	-10.1 (-3.08)	-10.1 (-3.08)	-11.0 (-3.35)	-.6 (-.18)	.0 (.00)	-2.6 (-.79)	-6.6 (-2.01)	-11.3 (-3.44)	-7.4 (-2.26)	-.1 (-.03)
		2	.0 GPR	-10.6 (-3.23)	-10.6 (-3.23)	-12.6 (-3.84)	-.3 (-.09)	-.1 (-.03)	-.9 (-.27)	-6.9 (-2.10)	-11.8 (-3.60)	-7.6 (-2.32)	-.1 (-.03)
		1	.0 FI	-10.1 (-3.08)	-10.1 (-3.08)	-11.0 (-3.35)	-.6 (-.18)	.0 (.0)	-2.6 (-.79)	-6.6 (-2.01)	-11.3 (-3.44)	-7.4 (-2.26)	-.1 (-.03)
6	e1,900	1	.0	-5.7 (-1.74)	-5.7 (-1.74)	-17.2 (-5.24)	-2.0 (-.61)	-2.2 (-.67)	-.6 (-.18)	-4.7 (-1.43)	-7.9 (-2.41)	-7.0 (-2.13)	.0 (.00)
7	e6,400	1	.0	-10.0 (-3.05)	-10.0 (-3.05)	-33.0 (-10.06)	-5.5 (-1.68)	-2.5 (-.76)	-9.0 (-2.74)	-7.4 (-2.26)	-15.8 (-4.82)	-10.1 (-3.08)	-.7 (-.21)
8	e3,000	1	0.0	-8.5 (-2.59)	-8.8 (-2.68)	-21.6 (-6.58)	-4.0 (-1.22)	-2.5 (-.76)	-7.1 (-2.16)	-7.9 (-2.41)	-13.7 (-4.18)	-8.3 (-2.53)	-0.1 (-.03)

Table 9. Residual depths of pier scour computed by use of each equation for bridge sites examined with Ground-Penetrating Radar and fixed instruments in New Hampshire—Continued

Site No. (fig. 1)	Discharge, in ft^3/s	Pier No.	Scour depth, in ft (m)	Residual depths of pier scour, in feet and meters, by equation name									
				HEC-18	CSU	Ahmad	Blench-Inglis II	Simplified Chinese	Melville-Sutherland	Shen	Shen-Maza	Jain-Fischer	New York 1996
9	44,300	2	0.0	-10.5 (-3.20)	-11.6 (-3.54)	-32.7 (-9.97)	-1.9 (-0.58)	-3.4 (-1.04)	-9.6 (-2.93)	-7.6 (-2.32)	-16.1 (-4.91)	-12.9 (-3.93)	-0.5 (-.15)
		3	.0	-10.3 (-3.14)	-11.6 (-3.54)	-32.6 (-9.94)	-1.7 (-.52)	-3.3 (-1.01)	-9.2 (-2.80)	-7.5 (-2.29)	-16 (-4.88)	-12.9 (-3.93)	-.5 (-.15)
10	44,300	2	.0	-10.7 (-3.26)	-12.0 (-3.66)	-37.0 (-11.28)	-.6 (-.18)	-3.5 (-1.07)	-5.5 (-1.68)	-7.7 (-2.35)	-16.3 (-4.97)	-13.9 (-4.24)	-.8 (-.24)
		3	.0	-7.0 (-2.13)	-10.0 (-3.05)	-22.3 (-6.80)	-1.0 (-.30)	-2.2 (-.67)	-7.1 (-2.16)	-6.4 (-1.95)	-13.3 (-4.05)	-10.8 (-3.29)	-.1 (-.03)
11	44,300	2	1.7	-13.7 (-4.18)	-13.7 (-4.18)	-24.3 (-7.41)	-3.7 (-1.13)	-2.0 (-.61)	-15.1 (-4.60)	-11.0 (-3.35)	-26.3 (-8.02)	-19.3 (-5.88)	1.5 (.46)
		3	2.3	-13.1 (-3.99)	-13.1 (-3.99)	-31.0 (-9.45)	-3.8 (-1.16)	-2.7 (-.82)	-14.7 (-4.48)	-11.7 (-3.57)	-28.7 (-8.75)	-24.5 (-7.47)	1.7 (.52)
12	e4,900	1	2.0	-8.4 (-2.56)	-8.4 (-2.56)	-13.9 (-4.24)	-10.2 (-3.11)	-3.6 (-1.10)	-11.6 (-3.54)	-5.2 (-1.58)	-11.9 (-3.63)	-8.5 (-2.59)	-25 (-7.62)
13	3,940	1	.0	-7.5 (-2.29)	-7.5 (-2.29)	-7.1 (-2.16)	-2.5 (-.76)	-1.8 (-.55)	-8.3 (-2.53)	-5.8 (-1.77)	-9.8 (-2.99)	-6.0 (-1.83)	.2 (.06)
		2	.0	-8.3 (-2.53)	-8.3 (-2.53)	-9.3 (-2.83)	.2 (.06)	-1.5 (-.46)	-20.5 (-6.25)	-5.8 (-1.77)	-9.8 (-2.99)	-7.1 (-2.16)	.1 (.03)
14	3,940	1	.0	-6.5 (-1.98)	-6.5 (-1.98)	-5.3 (-1.62)	-2.7 (-.82)	-1.9 (-.58)	-.7 (-.21)	-5.5 (-1.68)	-9.2 (-2.80)	-6.1 (-1.86)	.2 (.06)
		2	.0	-7.8 (-2.38)	-7.8 (-2.38)	-5.3 (-1.62)	.2 (.06)	-1.3 (-.40)	-18.9 (-5.76)	-5.5 (-1.68)	-9.2 (-2.80)	-6.7 (-2.04)	.1 (.03)
15	2,020	1	.0	-7.2 (-2.19)	-8.0 (-2.44)	-17.3 (-5.27)	-4.1 (-1.25)	-1.8 (-0.55)	-5.9 (-1.80)	-7.4 (-2.26)	-14.1 (-4.30)	-8.3 (-2.53)	.0 (.0)
16	4,450	1	1.4	-6.0 (-1.83)	-6.0 (-1.83)	-15.1 (-4.60)	-0.1 (-.03)	-.3 (-.09)	0.9 (.27)	-4.8 (-1.46)	-9.1 (-2.77)	-7.7 (-2.35)	1.4 (.43)
17	e1,300	1	.0	-8.7 (-2.65)	-10.1 (-3.08)	-17.4 (-5.30)	-4.9 (-1.49)	-2.6 (-.79)	-5.0 (-1.52)	-9.3 (-2.83)	-20.1 (-6.13)	-11.0 (-3.35)	.0 (.00)
18	3,940	1	.0	-4.8 (-1.46)	-4.8 (-1.46)	-15.0 (-4.57)	-.7 (-.21)	-1.8 (-.55)	-1.5 (-.46)	-3.9 (-1.19)	-6.3 (-1.92)	-5.7 (-1.74)	-.1 (-.03)

Table 9. Residual depths of pier scour computed by use of each equation for bridge sites examined with Ground-Penetrating Radar and fixed instruments in New Hampshire—Continued

Site No. (fig. 1)	Discharge, in ft^3/s	Pier No.	Scour depth, in ft (m)	Residual depths of pier scour, in feet and meters, by equation name									
				HEC-18	CSU	Ahmad	Blench-Inglis II	Simplified Chinese	Melville-Sutherland	Shen	Shen-Maza	Jain-Fischer	New York 1996
19	e2,000	1	0.0	-7.2 (-2.19)	-7.2 (-2.19)	-11.1 (-3.38)	-3.7 (-1.13)	-2.4 (-.73)	-11.4 (-3.47)	-7.7 (-2.35)	-6 (-1.83)	-8.1 (-2.47)	.1 (.03)
		2	.0	-7.2 (-2.19)	-7.2 (-2.19)	-11.1 (-3.38)	-3.7 (-1.13)	-2.4 (-.73)	-11.4 (-3.47)	-7.7 (-2.35)	-6.0 (-1.83)	-8.1 (-2.47)	.1 (.03)
20	e2,000	1	.0	-7.2 (-2.19)	-7.2 (-2.19)	-9.6 (-2.93)	-2.9 (-.88)	-2.0 (-.61)	-10.1 (-3.08)	-6.4 (-1.95)	-13.5 (-4.11)	-7.8 (-2.38)	.1 (.03)
		2	.0	-7.2 (-2.19)	-7.2 (-2.19)	-9.6 (-2.93)	-2.9 (-.88)	-2.0 (-.61)	-10.1 (-3.08)	-6.4 (-1.95)	-13.5 (-4.11)	-7.8 (-2.38)	.1 (.03)
Category				**Number of occurrences in each category of 32 observations by equation**									
Median				-8.6 (-2.62)	-9.5 (-2.90)	-15.0 (-4.57)	-2.8 (-.85)	-2.2 (-.67)	-9.1 (-2.77)	-6.8 (-2.07)	-12.2 (-3.72)	-8.0 (-2.44)	.0 (.0)
Interquartile range				-7.0 to -10.6 (-2.13 -3.23)	-6.5 to -10.9 (-2.90 to -3.32)	-9.5 to -21.4 (-2.90 to -6.52)	-.3 to -4.1 (-.09 to -1.25)	-1.5 to -2.7 (-.46 to -.82)	-2.6 to -11.6 (-.79 to -3.54)	-5.6 to -7.6 (-1.71 to -2.32)	-9.2 to -15.8 (-2.80 to 4.82)	-7.0 to -11.0 (-2.13 to -3.35)	.2 to -01 (.06 to -.03)
Residuals less than -10 ft (-3.05 m)				13	14	24	1	0	14	4	21	11	2
Residuals between -5 and -10 ft (-1.52 to -3.05 m)				18	17	7	6	4	9	24	10	21	1
Residuals between 0 and 5 ft (0.0 to -1.52 m)				1	1	1	22	27	8	4	1	0	16
Residuals greater than 0 ft (underestimates)				0	0	0	3	1	1	0	0	0	13

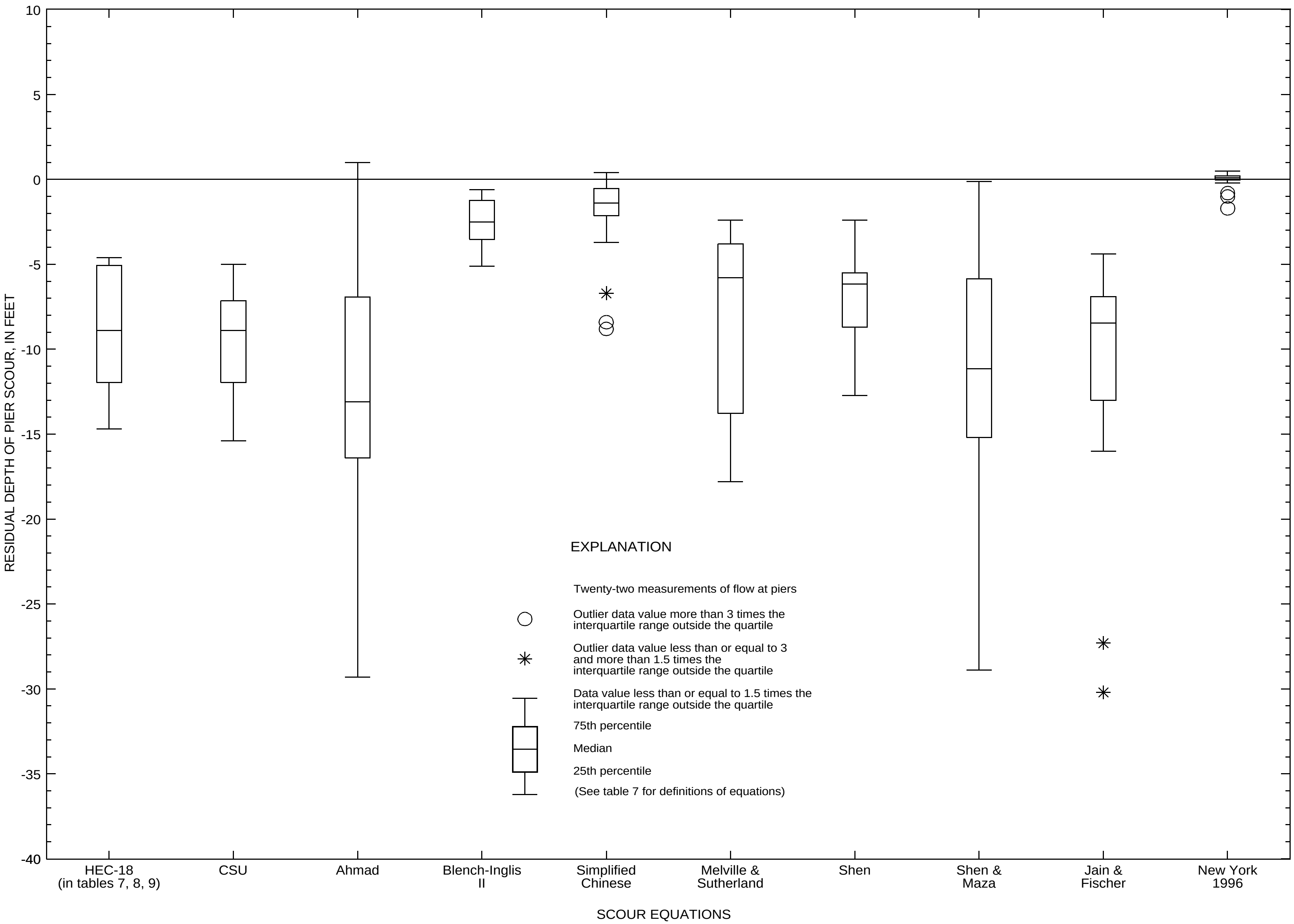

Figure 4. Residuals of pier-scour depths estimated/predicted by indicated equation and measured by field teams at five bridge sites in New Hampshire.

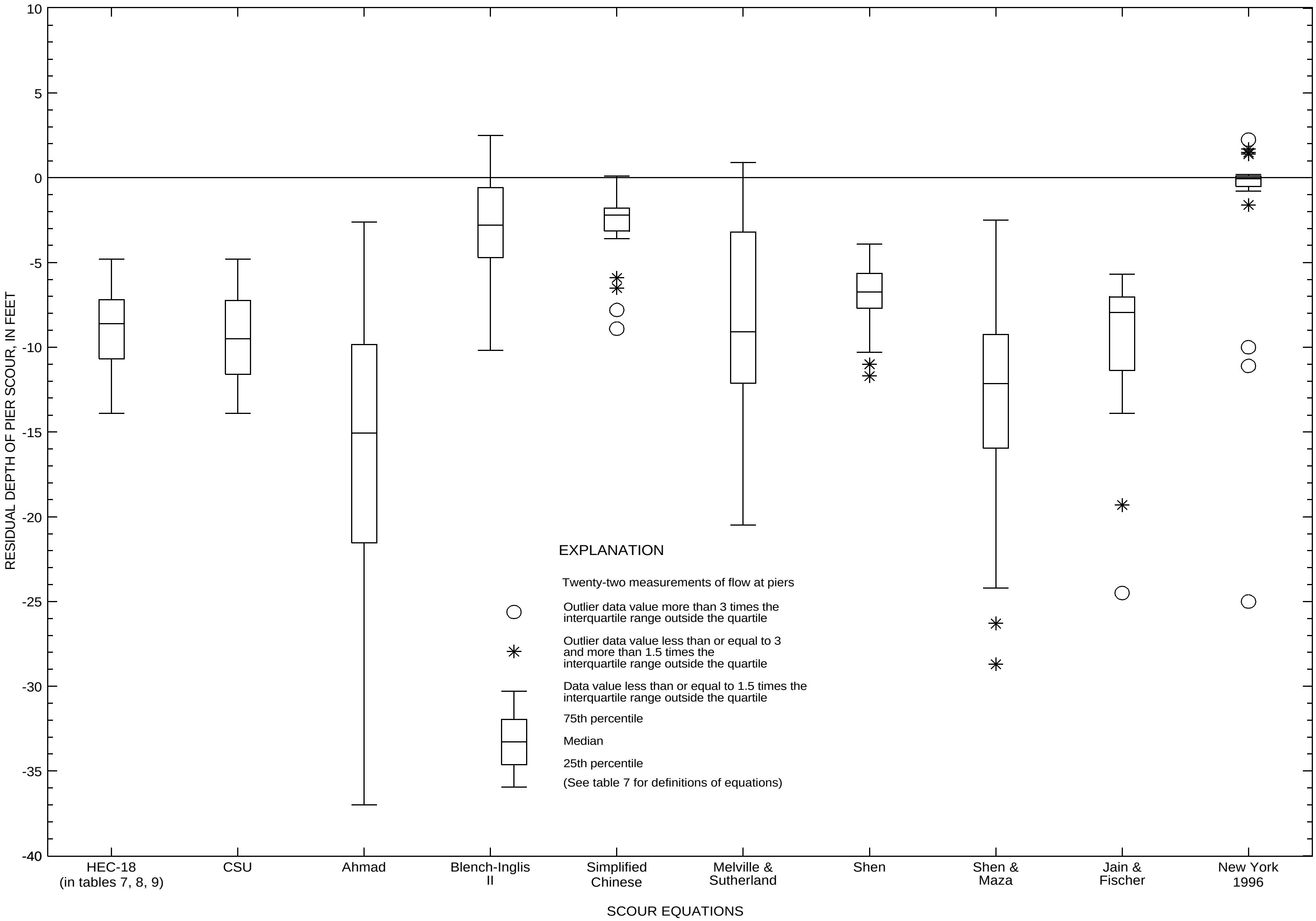

Figure 5. Residuals of pier-scour depths estimated/predicted by indicated equation and measured by Ground-Penetrating Radar and fixed instruments at 20 bridge sites in New Hampshire.

Distributions of the velocities and depths used for predicting pier scour at the six sites with measurable scour (sites 1, 3, 4, 11, 12, 16, table 3), are shown in boxplots (fig. 6) and provide an indication of the limited range of conditions available for examination in this study. With measurable scour only at six sites, none of the 10 equations examined can be recommended as the most appropriate for predicting the depth of scour for all bridge sites throughout New Hampshire. Scour-data collection at more bridge sites and during additional floods with greater discharges, depths, and velocities, would be necessary to support the effectiveness of a particular pier-scour prediction equation for sites in New Hampshire.

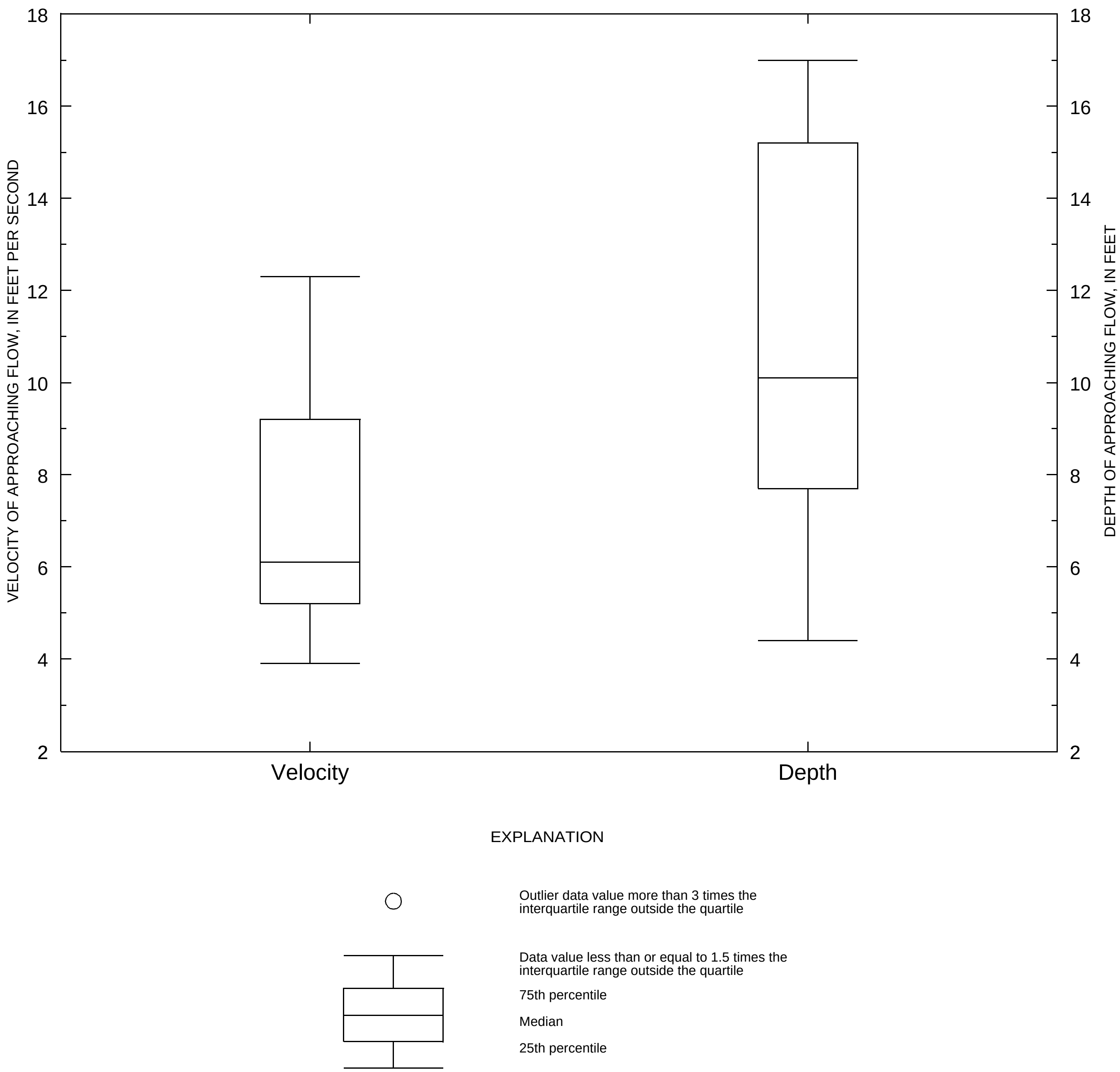

Figure 6. Boxplots of flow-approach velocities and depths (seven each) at piers with measurable scour in New Hampshire.

SUMMARY AND CONCLUSION

From April 1996 through November 1998, pier-scour measurements were made by flood teams at five bridge sites, by Ground-Penetrating Radar (GPR) at 20 sites, and by fixed instruments at 4 sites in New Hampshire. Streamflow in excess of the 2-year recurrence interval discharge was considered an acceptable minimum for flood-team measurements. Measurements by GPR were made at the beginning of the project period and again near the end. Fixed instruments provided continuous measurements and records of scour.

This report documents and compares the methods by which pier-scour measurements were made and compares measurements of pier-scour depth with pier scour predicted by use of 10 equations. These 10 equations were used to estimate pier scour for all 20 sites. Measurements by flood teams identified scour at only one of five sites, the bridge on State Route 18 across the Connecticut River in Littleton. Scour depths of 0.7 ft (0.21 m) were measured at each of two piers at this site on April 2, 1998. GPR records identified new scour during the study period at five of the 20 sites. Scour depths at these sites ranged from 1.1 ft (0.34 m) to 2.3 ft (0.70 m). Fixed instruments at two of four sites recorded changes in streambed elevations. However, changes at only one of these sites (at the U.S. Route 3 bridge crossing the Connecticut River in Clarksville) was attributed to scour. The scour depth recorded at this site was 0.7 ft (0.21 m) on April 1, 1998.

Study analyses consisted of computing and graphically comparing residuals between measured scour depths and scour depths predicted by the selected equations. Evaluating pier-scour depths involved establishing a scour-reference surface at each pier and determining the difference in scour depth between measurements at each pier. Pier-scour depths were computed by use of the following prediction equations: HEC-18, CSU, Ahmad, Blench-Inglis II, Simplified Chinese, Melville-Sutherland, Shen, Shen-Maza, Jain-Fischer, and New York 1996. Most pier-scour prediction equations were selected from a set of equations previously documented in the literature.

Streamflow discharges, velocities and depths were measured by flood teams or estimated from nearby stream-gaging stations and available hydraulic models for flood events at each site during the study period (April 1996 through November 1998). At most sites, no scour was measured and thus comparisons of residuals show how well equations predict zero scour. At those sites with measurable scour, the Shen, Blench-Inglis II, and Simplified Chinese equations closely predicted pier-scour depths. The narrow range of residual scour depth with the Simplified Chinese equation may be attributed to the velocity-ratio variable contribution to the scour depth. With this ratio, the Simplified Chinese equation accounts for the competence of the flow, which is not a concept incorporated in most of the other equations examined. Additional measurements at more sites and higher flood flows would be needed to establish the superiority of any specific equation for general use in New Hampshire.

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APPENDIX 1. Site Descriptions, Bridge Cross Sections, and Fixed-Instrument Measurements for Pier-Scour Study Sites in New Hampshire 1995-98

BRIDGE SITE DESCRIPTIONS

More details pertaining to the characteristics of each site are organized in tables 10, 11, and 12. The locations of each site, the terrain and development near each site, the valley setting and flood plain width at each site are summarized in table 10. Relief described under the valley setting as low, moderate, and high is associated with valley-to-ridge elevation changes of less than 30 m (98.4 ft), 30 to 300 m (98.4 to 984.3 ft), and greater than 300 m (984.3 ft) categories, respectively. Flood-plain widths designated "none" in table 10 indicates a width less than two times the width of the channel, "narrow" flood plains are between 2 times and 10 times the main channel width, and "wide" flood plains are greater than 10 times the main channel width.

Select characteristics of each bridge are listed in table 11. Values are in feet for the length and width of piers and the bridge and converted to meters in parentheses. The value for the median size of the bed material was measured in millimeters and converted to feet in parentheses. Angles of attack of the approaching flow were measured and provided in degrees. These data were compiled from the Level II bridge-scour evaluations and site assessments provided by the New Hampshire Department of Transportation in Whitman & Howard, Inc. (1992).

Select geomorphic characteristics of the stream and the channel near each site are listed in table 12. These are categorized and tabulated based on the discussion provided in HEC-20 (Lagasse and others, 1995). Waterway size is divided into three categories according to the width of the channel. Small waterways are less than 30 m (98.4 ft), medium waterways 30 to 150 m (98.4 to 492.2 ft), and large waterways are greater than 150 m (492.2 ft). Sinuosity is the ratio of the stream length to the valley length or flood-flow length. Sinuosity is a quantitative measure broken down into four categories in Lagasse and others (1995) and listed in table 12. Straight channels have a sinuosity between 1.0 and 1.05; sinuous channels have a sinuosity between 1.06 and 1.25; meandering channels have a sinuosity between 1.25 and 2.00; highly meandering channels have a sinuosity greater than 35.

BRIDGE CROSS SECTIONS

Compiled cross-section data with site condition descriptions at the time of the flood measurements are presented below by site. From 1996 through 1998, there were three measured floods; October 1996, April 1998, and June 1998.

Structure 160/188 on State Route 9 over the Soucook River in Concord, New Hampshire. Measurements of two floods at this site were made October 22 and 23, 1996, and June 16-18, 1998. Discharges ranged from 746 to 1,690 ft^3/s (21 to 48 m^3/s), and from 1,050 to 2,120 ft^3/s (30 to 60 m^3/s) for each flood respectively. Measurements were alternated between the upstream and downstream sides of the bridge. Debris accumulation on the piers did not complicate the taking of measurements at this site. The angle of attack observed at both piers was 5 degrees for all flood measurements (fig. 7).

Structure 110/190 on State Route 153 over the Ossipee River in Effingham, New Hampshire. One flood event was measured between June 15 and 19, 1998. Discharges ranged from 5,920 to 7,690 ft^3/s (168 to 218 m^3/s) for 10 measurements made during the flood. Discharge measurements were alternated between the upstream and downstream sides of the bridge. One whole tree lodged on the left pier sometime between the fourth and fifth measurements, but was floating and had no noticeable impact on scour at the streambed. Cross sections of the streambed for each measurement are provided in figure 8. The cross sections indicate the channel was stable throughout the flood.

Structure 109/134 on State Route 18 Over the Connecticut River in Littleton, New Hampshire. The most significant flood (reservoir release) during this study occurred on April 2-3, 1998. Discharges ranged from 30,300 to 44,300 ft^3/s (858 to 1,255 m^3/s) over 6 measurements. Two prior discharge measurements were made on April 30, 1996, in anticipation of more rain and an increased release rate from Moore Reservoir, which did not occur. These discharges were 11,400 and 14,800 ft^3/s (323 to 419 m^3/s). Discharge measurements for the flood were made on the upstream and downstream sides of the bridge at nearly the same time. Backwater from Comerford Dam downstream mostly affected the two measurements taken on April 3, 1998.

Elevations near piers were significantly higher than the adjacent streambed elevations from the design plans because of stone-fill protection placed around the piers prior to the structural inspection report in 1990. Measurements of attack angle on each pier were consistent with those applied for the Level II assessments (New Hampshire Department of Transportation, 1992). Cross sections of the streambed elevations across the upstream and downstream sides of the bridge are shown in figure 9.

Structure 146/100 on State Route 107 Over the Lamprey River in Raymond, New Hampshire. One flood occurred that was measured between October 22-24, 1996. Out of seven discharge measurements, only the second and seventh were conducted from the downstream side of the bridge. Discharges ranged from 716 to 2,020 ft^3/s (20 to 57 m^3/s) for the seven measurements conducted during the flood.

Cross sections of the channel from the upstream and downstream sides of the bridge are provided in figure 10.

Table 10. Site descriptions for 20 selected bridges examined in New Hampshire

[US, United States; I, interstate]

Site No. (fig. 1)	Structure No.	Town	Location	Nearby landmarks	Terrain	Development	Valley setting	Flood-plain width
1	076/080	Ashland	US 3/N.H. 25 over the Pemigewasset River	1.4 miles Northwest of the Post Office in Ashland and about 2.0 miles upstream of the confluence of the Squam River	Hilly to mountainous	Rural	V-shaped, moderate relief	None
2	183/087	Bristol	N.H. 104 over the Pemigewasset River	West 0.6 mile from downtown New Hampton and 3.4 miles upstream of the powerplant dam near downtown Bristol	Hilly to mountainous	Locally residential and commercial	V-shaped, moderate relief	None
3	030/066	Clarksville	US 3 over the Connecticut River	Downstream 2.0 miles from the confluence of Indian Stream and 2.0 miles Northeast of Beecher Falls Village in Canaan, Vt.	Hilly to mountainous	Rural	U-shaped, high relief	None
4	160/188	Concord	N.H. 9 over the Soucook River	Upstream 0.9 mile from the confluence of Cemetary Brook and 4.4 miles northeast of the State Capitol in Concord	Rolling to hilly	Rural	V-shaped, moderate relief	None to narrow
5	110/190	Effingham	N.H. 153 over the Ossipee River	Downstream 0.3 mile of the streamgage, 0.4 mile downstream from the outlet of Ossipee Lake (Berry Bay), and 4.0 miles Northwest of Effingham	Hilly to mountainous	Locally residential	U-shaped, moderate relief	None
6	096/140	Farmington	N.H. 153 over the Cocheco River	At the south end of downtown Farmington and 0.4 mile downstream of the confluence of the Mad River	Hilly to mountainous	Locally residential and commercial	V-shaped, moderate relief	None to narrow
7	046/178	Jefferson	US 2 over the Israel River	At the village of Riverton in Jefferson, 2.1 miles east of the lookout tower on Prospect Mountain and about 3.4 miles upstream of the confluence of Otter Brook	Hilly to mountainous	Rural residential	U-shaped, moderate relief	None to narrow
8	202/100	Lincoln	I-93 Northbound Exit Ramp over the Pemigewasset River	Upstream 2.6 miles of the confluence of the East Branch Pemigewasset River and 1.5 miles South of the outlet of Shadow Lake	Mountainous	Locally residential and commercial	V-shaped, high relief	None
9	104/136	Littleton	I-93 Southbound over the Connecticut River	Downstream 0.9 mile from Moore Reservoir, 1.2 miles southeast of Lower Waterford, Vt., and 2.3 miles North of Partridge Lake	Mountainous	Rural	V-shaped, moderate relief	None
10	105/135	Littleton	I-93 Northbound over the Connecticut River	Downstream 0.9 mile from Moore Reservoir, 1.2 miles southeast of Lower Waterford, Vt., and 2.3 miles North of Partridge Lake	Mountainous	Rural	V-shaped, moderate relief	None
11	109/134	Littleton	N.H. 18 over the Connecticut River	Downstream 0.8 mile from Moore Reservoir, 1.2 miles southeast of Lower Waterford, Vt., and 2.3 miles North of Partridge Lake	Mountainous	Rural	V-shaped, moderate relief	None

Table 10. Site descriptions for 20 selected bridges examined in New Hampshire—Continued

Site No. (fig. 1)	Structure No.	Town	Location	Nearby landmarks	Terrain	Development	Valley setting	Flood-plain width
12	123/133	Milford	N.H. 13 over the Souhegan River	South 2.0 miles from the outlet of Hartshorn Pond and 1.6 miles downstream of the confluence of Tucker Brook	Rolling to hilly	Locally suburban residential and commercial	U-shaped, moderate relief	Narrow
13	117/157	Northfield	I-93 Southbound over the Winnipesaukee River	Upstream 1.2 miles from the streamgage at Tilton, and 1.4 miles downstream from the confluence of the Tioga River	Rolling to hilly	Commercial and some residential	V-shaped, moderate relief	None
14	118/158	Northfield	I-93 Northbound over the Winnipesaukee River	Upstream 1.2 miles from the streamgage at Tilton, and 1.4 miles downstream from the confluence of the Tioga River	Rolling to hilly	Commercial and some residential	V-shaped, moderate relief	None
15	146/100	Raymond	N.H. 107 over the Lamprey River	Upstream 0.5 mile from Dead Pond and 1 mile southeast of Raymond	Hummocky	Rural residential	V-shaped, low relief	None
16	238/092	Sandwich	N.H. 113 over the Cold River	Upstream 0.8 mile from the mouth at the Bearcamp River and 2.5 miles Northwest of South Tamworth	Hilly to mountainous	Rural	U-shaped, moderate relief	Wide
17	093/061	Sullivan	N.H. 9 over Otter Brook	At East Sullivan, 2.5 miles southwest of Granite Lake and 1.0 mile upstream from the confluence of Hubbard Brook	Rolling to hilly	Rural residential	V-shaped, moderate relief	None
18	109/062	Tilton	N.H. 140 over the Winnipesaukee River	Upstream 1.6 miles from the streamgage at Tilton, and 1.0 mile downstream from the confluence of the Tioga River	Rolling to hilly	Commercial and some residential	U-shaped, moderate relief	Narrow
19	166/103	Warner	I-89 Southbound over the Warner River	Upstream 150 feet from the confluence of Stevens Brook and 0.9 mile east of Waterloo	Rolling to hilly	Rural	U-shaped, moderate relief	Narrow
20	166/104	Warner	I-89 Northbound over the Warner River	Upstream 150 feet from the confluence of Stevens Brook and 0.9 mile east of Waterloo	Rolling to hilly	Rural	U-shaped, moderate relief	Narrow

Table 11. Bridge descriptions for 20 selected sites examined in New Hampshire

[Number in ( ), is in meters]

Site No. (fig. 1)	Structure No.	Town	Year built	Length, in feet (meters)	Width, in feet (meters)	Average daily traffic	Pier nose shape	Pier length, in feet (meters)	Pier width, in feet (meters)	D_{50} in millimeters (inches)	Flow angle of attack, in degrees
1	076/080	Ashland	1937	800 (234)	27 (8.23)	2,600	Round	37.0 (11.3)	10.0 (3.05)	50 (0.164)	5
2	183/087	Bristol	1985	408 (124)	43 (13.1)	6,700	Sharp	36.0 (11.0)	6.0 (1.83)	0.47 (.00154)	0
3	030/066	Clarksville	1931	221 (67.4)	24 (7.32)	1,300	Sharp	46.0 (14.0)	4.6 (1.40)	28 (.0919)	5
4	160/188	Concord	1936	178 (54.2)	44 (13.4)	5,400	Square	61 (18.6)	5.0 (1.52)	7.5 (.0246)	5
5	110/190	Effingham	1956	242 (73.8)	24.0 (7.32)	200	Sharp	25.0 (7.62)	2.0 (.61)	55 (.180)	15
6	096/140	Farmington	1924	48 (14.6)	26 (7.92)	8,810	Sharp	41.0 (12.5)	3.0 (.91)	25 (.082)	0
7	046/178	Jefferson	1974	164 (50.0)	42.5 (13.0)	3,900	Sharp	56.0 (17.1)	4.5 (1.37)	53 (.174)	0
8	202/100	Lincoln	1973	253 (77.1)	27.0 (8.23)	8,300	Sharp	46.2 (14.1)	4.7 (1.43)	80 (.262)	0
9	104/136	Littleton	1981	668 (204)	41.0 (12.5)	1,720	Sharp	30.0 (9.14)	6.3 (1.92)	80 (.262)	0
10	105/135	Littleton	1976	670 (204)	41.0 (12.5)	1,720	Sharp	30.0 (9.14)	6.3 (1.92)	80 (.262)	0
11	109/134	Littleton	1934	530 (162)	26.5 (8.08)	750	Round	42.0 (12.8)	6.4 (1.95)	80 (.262)	15
12	123/133	Milford	1931	112 (34.1)	30.0 (9.14)	13,200	Sharp	40.0 (12.2)	8.0 (2.44)	0.37 (.00121)	0
13	117/157	Northfield	1960	342 (104)	46.5 (14.1)	9,310	Sharp	38.0 (11.6)	5.0 (1.52)	16 (.0525)	5
14	118/158	Northfield	1960	333 (101)	38.0 (11.6)	9,310	Sharp	31.5 (9.60)	5.0 (1.52)	16 (.0525)	5

Table 11. Bridge descriptions for 20 selected sites examined in New Hampshire—Continued

Site No. (fig. 1)	Structure No.	Town	Year built	Length, in feet (meters)	Width, in feet (meters)	Average daily traffic	Pier nose shape	Pier length, in feet (meters)	Pier width, in feet (meters)	D_{50} in millimeters (inches)	Flow angle of attack, in degrees
15	146/100	Raymond	1962	94 (28.7)	50.0 (15.2)	1,100	Sharp	38.0 (11.6)	2.5 (.76)	65 (.213)	5
16	238/092	Sandwich	1958	146 (44.5)	32.0 (9.75)	450	Sharp	33.0 (10.0)	2.5 (0.76)	38 (.125)	5
17	093/061	Sullivan	1932	92.0 (28.0)	25.0 (7.62)	3,410	Sharp	49.0 (14.9)	2.0 (.61)	79 (.259)	10
18	109/062	Tilton	1968	132 (40.2)	40.0 (12.2)	3,080	Sharp	48.0 (14.6)	2.5 (.76)	30 (.0984)	0
19	166/103	Warner	1966	191 (58.2)	52.0 (15.8)	7,450	Cylinder	67.0 (20.4)	3.0 (.91)	21 (.0689)	10
20	166/104	Warner	1966	161 (49.1)	38.0 (11.6)	7,450	Cylinder	49.5 (15.1)	3.0 (.91)	21 (.0689)	10

Table 12. Waterway descriptions for 20 selected bridge sites examined in New Hampshire

Site No. (fig. 1)	Structure No.	Town	Size	Type of river	Bed material	Boundaries	Incision	Sinuosity	Width variation	Bar development
1	076/080	Ashland	Medium	Perennial	Cobbles	Semi-alluvial	Locally incised	Sinuous	Constant width	Narrow bars
2	183/087	Bristol	Medium	Perennial	Sand	Semi-alluvial	Not incised	Sinuous	Constant width	Narrow bars
3	030/066	Clarksville	Medium	Perennial	Gravel	Non-alluvial	Locally incised	Sinuous	Constant width	Narrow bars
4	160/188	Concord	Small	Perennial	Sand	Semi-alluvial	Locally incised	Sinuous	Randomly varying	Irregular
5	110/190	Effingham	Small	Perennial	Gravel/cobbles	Non-alluvial	Not incised	Sinuous	Randomly varying	Irregular
6	096/140	Farmington	Small	Perennial	Gravel	Non-alluvial	Locally incised	Sinuous to meandering	Constant width	Narrow bars
7	046/178	Jefferson	Small	Perennial	Gravel/cobbles	Non-alluvial	Not incised	Meandering	Wider at bends	Wide bars
8	202/100	Lincoln	Small	Perennial	Cobbles	Non-alluvial	Not incised	Meandering	Wider at bends	Wide bars
9	104/136	Littleton	Medium	Perennial	Cobbles/gravel	Non-alluvial	Incised	Straight	Constant width	None
10	105/135	Littleton	Medium	Perennial	Cobbles/gravel	Non-alluvial	Incised	Straight	Constant width	None
11	109/134	Littleton	Medium	Perennial	Cobbles/gravel	Non-alluvial	Incised	Straight	Constant width	None
12	123/133	Milford	Small	Perennial	Sand	Semi-alluvial	Not-incised	Meandering	Constant width	Narrow
13	117/157	Northfield	Small	Perennial	Gravel	Semi-alluvial	Locally incised	Sinuous	Constant width	None
14	118/158	Northfield	Small	Perennial	Gravel	Semi-alluvial	Locally incised	Sinuous	Constant width	None
15	146/100	Raymond	Small	Perennial	Gravel/cobbles	Non-alluvial	Locally incised	Sinuous	Randomly varying	Irregular
16	238/092	Sandwich	Small	Perennial	Gravel	Semi-alluvial	Not incised	Sinuous	Wider at bends	Wide bars
17	093/061	Sullivan	Small	Perennial	Cobbles	Non-alluvial	Locally incised	Sinuous	Constant width	Narrow bars
18	109/062	Tilton	Small	Perennial	Gravel	Semi-alluvial	Not incised	Sinuous	Constant width	None
19	166/103	Warner	Small	Perennial	Gravel	Semi-alluvial	Locally incised	Straight	Constant width	None
20	166/104	Warner	Small	Perennial	Gravel	Semi-alluvial	Locally incised	Straight	Constant width	None

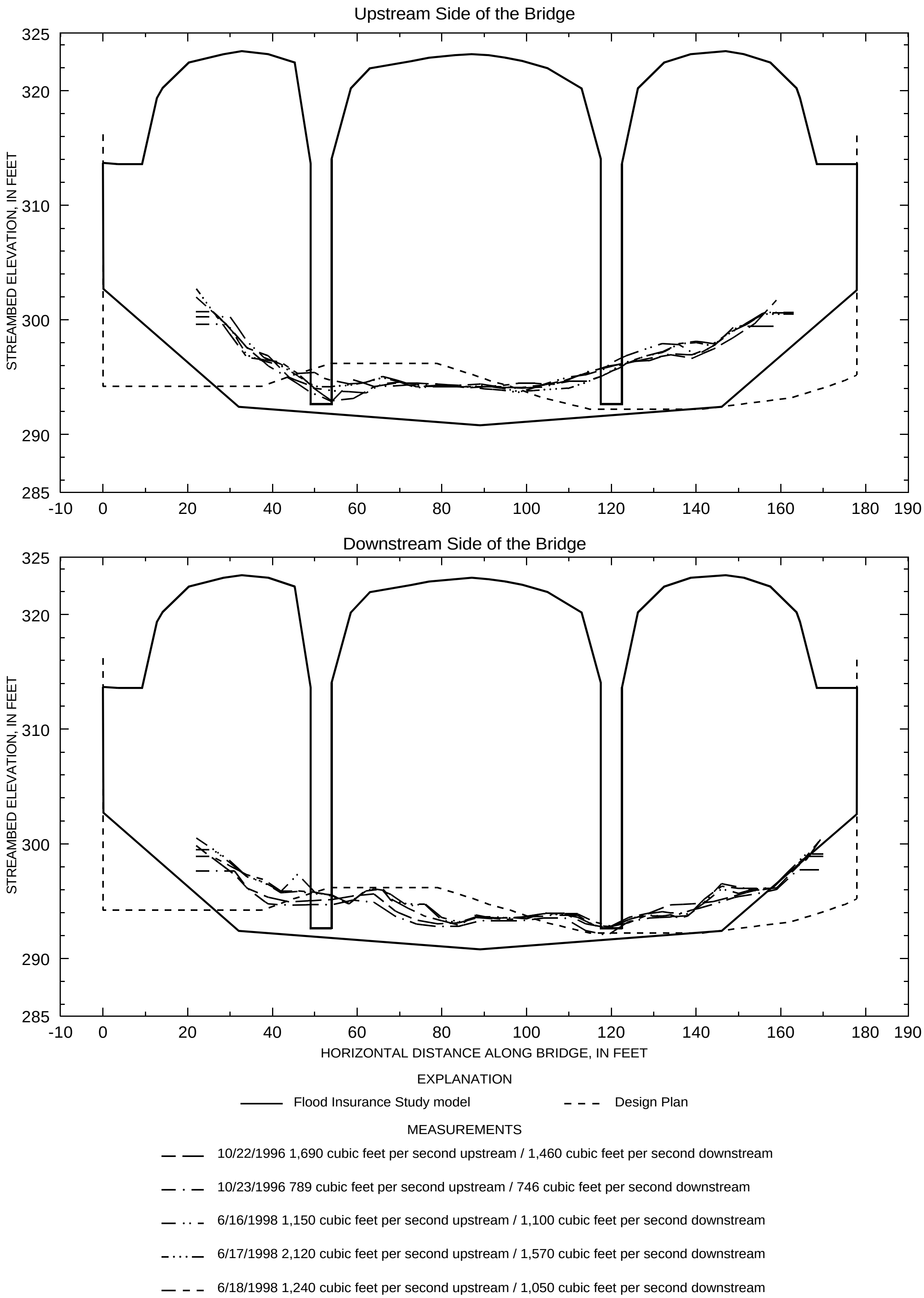


Figure 7. Cross sections of the channel along the upstream and downstream sides of the bridge on State Route 9 over the Soucook River in Concord, N.H., measured during floods and extracted from design plans and the Flood Insurance Study model. (Site location shown in figure 1.)

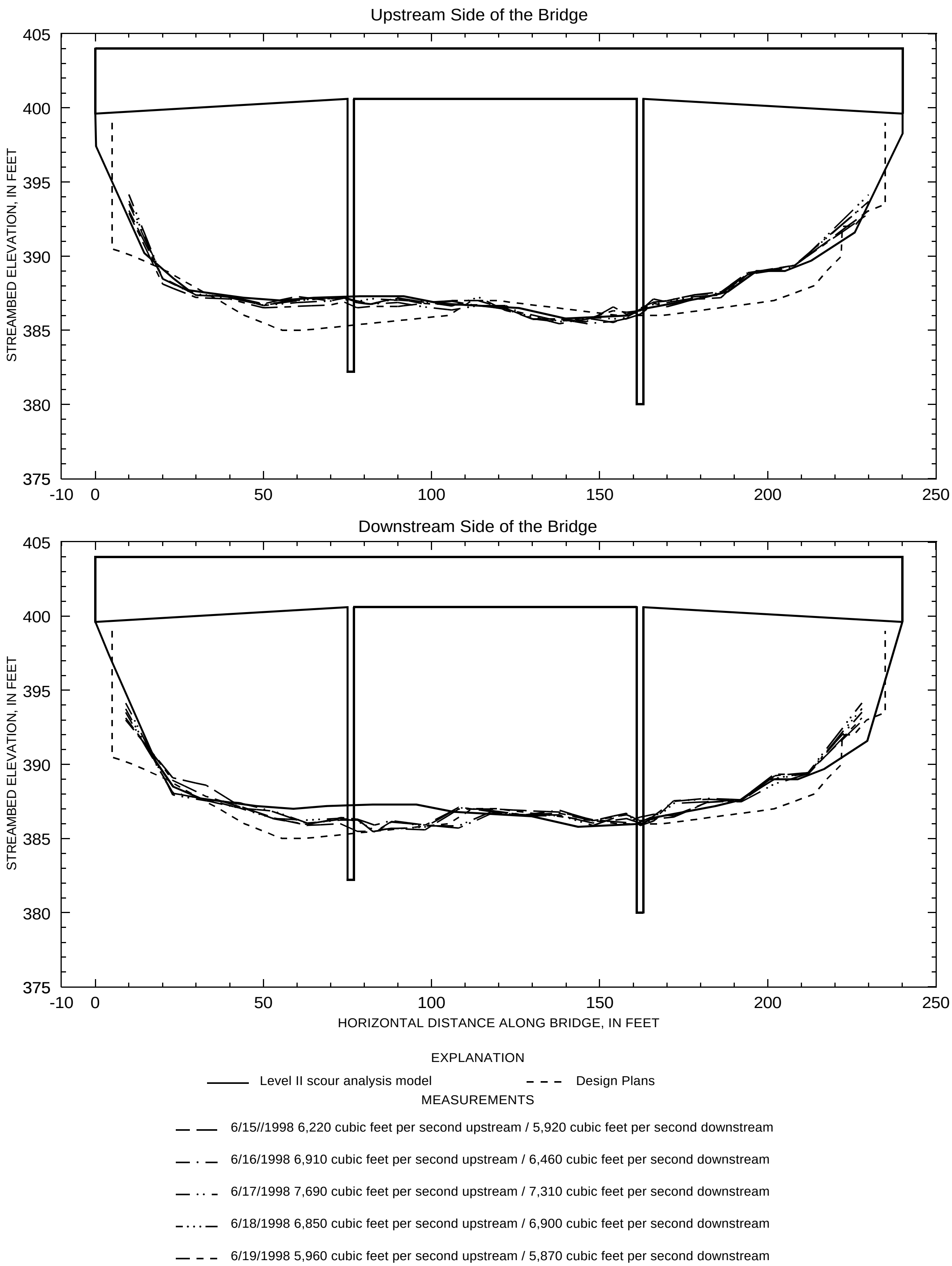
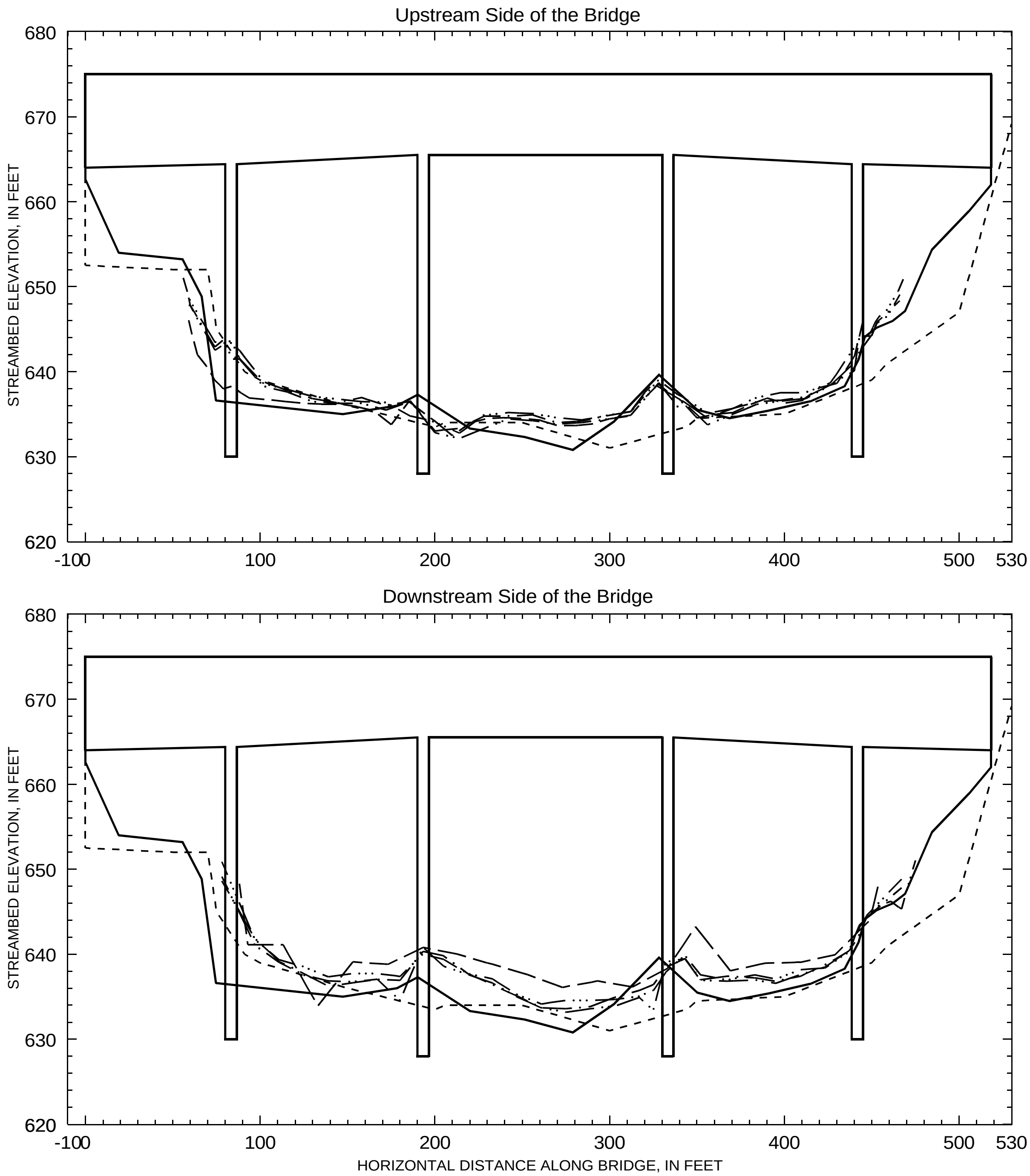


Figure 8. Cross sections of the channel along the upstream and downstream sides of the bridge on State Route 153 over the Ossipee River in Effingham, N.H., measured during floods and extracted from design plans and the Level II scour-analysis model. (Site location shown in figure 1.)



EXPLANATION

Level II scour-analysis model — Design Plans

MEASUREMENTS

4/30/1996 14,800 cubic feet per second upstream / 11,400 cubic feet per second downstream

4/2/1998 38,700 cubic feet per second upstream / 36,700 cubic feet per second downstream

4/2/1998 44,300 cubic feet per second upstream / 40,200 cubic feet per second downstream

4/3/1998 33,800 cubic feet per second upstream / 30,300 cubic feet per second downstream

Figure 9. Cross sections of the channel along the upstream and downstream sides of the bridge on State Route 18 over the Connecticut River in Littleton, N.H., measured during floods and extracted from design plans and the Level II scour-analysis model. (Site location shown in figure 1.)

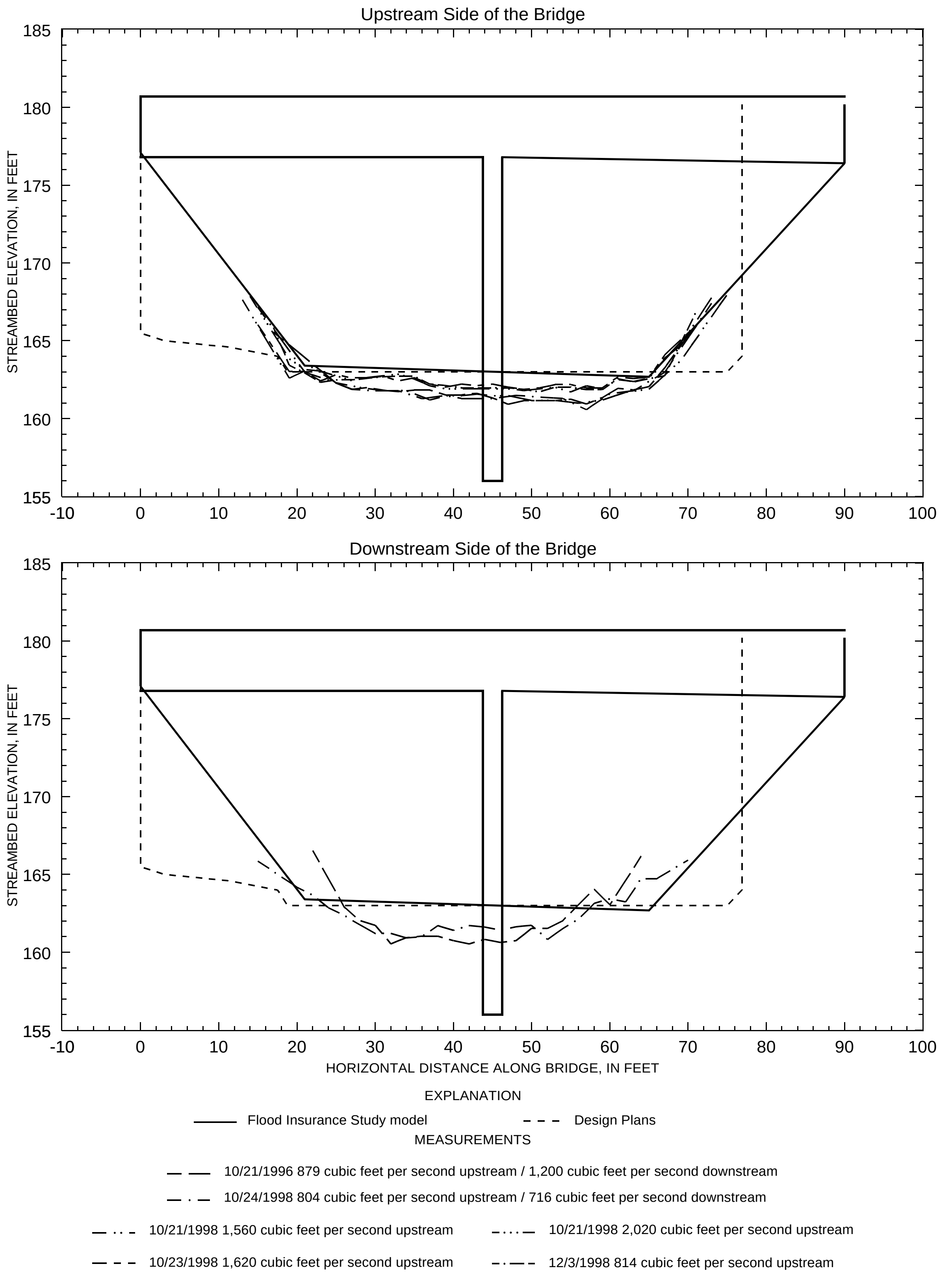


Figure 10. Cross sections of the channel along the upstream and downstream sides of the bridge on State Route 107 over the Lamprey River in Raymond, N.H., measured during floods and extracted from design plans and the Flood Insurance Study model. (Site location shown in figure 1.)

Elevations from flood-insurance-study sections and from contour lines drawn on design plans did not include elevations below the water surface.

Structure 238/092 on State Route 113 Over the Cold River in Sandwich, New Hampshire. Discharge of the flood between June 14-15, 1998, was measured alternating between the upstream and downstream sides of the bridge. Discharges ranged from 1,220 to 4,450 ft^3/s (35 to 126 m^3/s) over 5 measurements. There was no debris or other measurement complication during the flood.

Cross sections of the channel from the upstream and downstream sides of the bridge are shown in figure 11. The cross sections at the downstream side of the bridge show no changes in elevation throughout the entire section. A comparison of the cross sections on the upstream side shows the channel at the bridge appears to have filled in. The consistent difference of the elevations at measurement points suggests that the change is due to an error in the water-surface elevation.

FIXED-INSTRUMENT MEASUREMENT SITES

Route 3 Bridge over the Connecticut River. At the Route 3 Bridge over the Connecticut River in Clarksville, is an 8-degree transducer that was installed in October 1996, at 5.5 ft (1.67 m) above the existing streambed. From October 1996 to February 1998, the transducer yielded no data because the stream stage was not high enough to submerge the face of the transducer. From March 31 through April 2, 1998, a flood estimated to equal or exceed the flood at the 75-year recurrence interval occurred. The fixed instrument measured a maximum depth of 6.2 ft (1.88 m) on April 1, which equals 0.7 ft (0.21 m) of scour.

No significant flood events occurred after the March-April flood event. The stage did not again get high enough to submerge the transducer during the remaining period of observation from May 1998 to April 1999.

Route 153 Bridge over the Ossipee River. At the Route 153 bridge over the Ossipee River in Effingham, an 8-degree transducer was originally installed in October 1996 at an elevation of 4.0 ft (1.22 m) above the existing bed bottom. From October 1996 to April 1997, no significant flood events occurred (2-year recurrence interval or greater) in which the stream stage was high enough to sufficiently submerge the transducer face to take streambed-depth measurements. From April 4 through May 5, 1997, water releases from the dam approximately 0.75 mi (1.21 km) upstream of this site at Ossipee Lake caused stream stage at the bridge site to rise enough to submerge the transducer. Continuous transducer depth measurements were recorded every half hour at the bridge pier indicating a maximum depth of 4.1 ft (1.25 m) (0.1 ft of scour) during this period. A subsequent field check of the instrument and manual measurement of the distance between the transducer and the streambed confirmed this depth.

No significant flood events occurred at this site from May 6, 1997 to March 25, 1998 and the stage did not get high enough to submerge the transducer. Later, from March 25 to May 14, 1998, water releases from the dam caused stream stage at the bridge site to rise enough to submerge the transducer. Continuous transducer depth measurements were recorded every half hour at the bridge pier. Streambed depths during this period ranged from 3.9 to 4.2 ft (1.19 to 1.28 m).

A flood event estimated to equal or exceed the 75-year recurrence interval occurred during the week of June 15-19, 1998. A peak flow of 7,690 ft^3/s (218 m^3/s) was measured on June 17. Continuous transducer depth measurements were recorded every half hour at the bridge pier. Depths ranged from 4.0 ft (1.22 m) on June 15 to 3.1 ft (0.94 m) on June 19. During this time the instrument measured a maximum depth of 4.2 ft (1.28 m). Sediment deposition did not occur. Due to the boulder streambed characteristics of the channel, however, this scour depth is deceiving. Large boulders up to 2 ft (0.61 m) in diameter, commonly 1 ft (0.30 m) in diameter, line the streambed beneath the bridge opening to include the streambed area beneath the transducer. Based on field observations, it was determined that the boulders had moved beneath the transducer and caused the apparent change in streambed elevation.

A subsequent field measurement was made after the flood on June 15, 1998. Manual measurement of the depth to the streambed beneath the transducer remained at 4.0 ft (1.22 m). No significant flood events occurred after the June flood event and the transducer was not submerged from July 1998 to April 1999.

Interstate Route 93 Northbound Exit Ramp 33 Bridge Over the Pemigewasset River. The Brisco monitor used at this site was not connected to a data recorder, therefore, depth measurements were recorded manually from the digital display and were made once every 3 months or immediately after a significant streamflow event. No change in the depth measurements were recorded over the observation period (December 1996 through April 1999).

State Route 18 Bridge Over the Connecticut River. At this site (site 11) in Littleton, N.H., transducers were mounted on piers 2 and 3 in October 1996. A gap in the record resulted from vandalism of the recording instrument in December 1997. Repairs to the instrument and reinstallation were completed in March 1998, prior to the flood at the beginning of April. The transducer on pier 2 (transducer #1) had a reading of 5.8 ft (1.78 m) to the stone

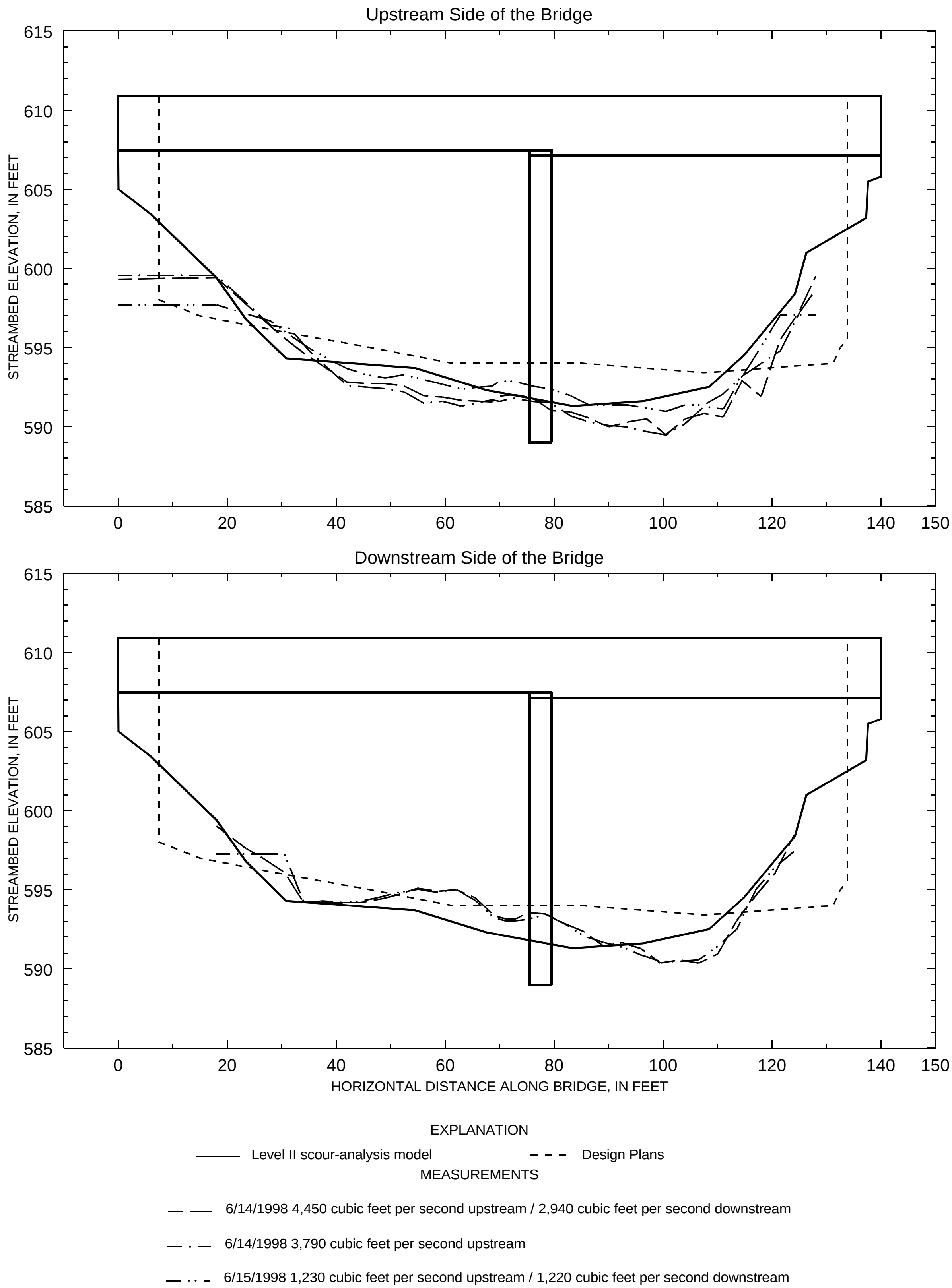


Figure 11. Cross sections of the channel along the upstream and downstream sides of the bridge on State Route 113 over the Cold River in Sandwich, N.H., measured during floods and extracted from design plans and the Level II scour-analysis model. (Site location shown in figure 1.)

fill protecting the pier footing at the time of installation. In April 1998, the depth measured by this instrument increased by 0.3 ft (0.10 m). This increase was associated with the flood event of April 2, 1998, which approximated a 50-year recurrence interval at the site. The change was the result of slumping of the stone fill at the pier footing. The transducer on pier 3 (transducer #2) had a reading of 5.2 ft (5.22 m) to the stone fill protecting the pier footing at the time of installation. Depth readings for this instrument had minor fluctuations during the observation period. However, no pier scour was observed by the instrument during the flood of April 1998. After this flood, the reading stabilized at 5.1 ft (1.55 m) within 0.1 ft (0.04 m) of the reading at the time of installation. Due to the nature of the stone-fill materials below these transducers, depth changes measured at this site were not used for comparison with scour depths estimated by equations evaluated in this report.

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